THE STRENGTH PREDICTION OF LAMINATED FINGER JOINTED EUCALYPTUS GRANDIS MEMBERS USING COMPUTER SIMULATION

by

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INDEX

OPSOMMING

Die sterkte voorspelling van gelamineerde *Eucalyptus grandis* elemente met vingerlasse met behulp van rekenaar simulasie.

deur

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Nadat die beperkings van die beskikbare sterkte data van Suid Afrikaanse *Eucalyptus grandis* bespreek is, stel die outeur moontlike navorsingsgebiede voor sodat groter sekerheid oor die sterkte eienskappe van bogenoemde materiaal verkry kan word. 'n Groter sekerheid oor die sterkte eienskappe van *Eucalyptus grandis* lei tot 'n betere begrip van die swigmeganismes van gelamineerde *Eucalyptus grandis* elemente. Die sterkte eienskappe van die materiaal en die moontlike korrelasie tussen hierdie eienskappe word benodig vir die simulasie van die gelamineerde elemente se sterkte.

Verskei laboratorium toetse is gebruik om die sterkte eienskappe van *Eucalyptus grandis* te bepaal en die word bespreek, die data word voorgelê en gevolgtrekkings oor die sterkte eienskappe soos elastisiteits modulus, treksterkte parallel aan die grein, trekstrekte loodreg op die grein en skuifsterkte word gemaak. Die belangrikheid van die sterkte eienskappe betreffende die swigting van gelamineerde elemente met vingerlasse word bespreek. Die korrelasie tussen die verskillende sterkte eienskappe, wat in die simulasie van gelamineerde elemente gebruik word, is bepaal. Verdere moontlike toetse asook toetsmetodes word aanbeveel.

Die simulasie metode word bespreek en 'n metode om willekeurige vingerlas sterktes, plank sterktes en plank styfheid te simuleer word aangebied. Hierdie metode word uitgebrei om gekorreleerde vingerlas sterktes, plank sterktes en plank styfheid te simuleer.

Die simulasie metode word gebruik om enkel lamel trekdele met vingerlasse te simuleer. Die aantal vingerlasse word gevarieër en gevolgtrekkings word gemaak oor die effek van vingerlasse op die sterkte van trekdele. Hierdie metode word dan toegepas op twee lamel trekdele en gevolgtrekkings word gemaak oor die verlies aan sterkte as gevolg van die vingerlasse in die element.

'n Simulasie metode word beskryf en gebruik om die moontlikke verswakkende effek van faktore soos die lengte, diepte en tipe belasting op die sterkte van gelamineerde buigelemente, met vingerlasse, te ondersoek. Dit word uitgespel dat die faktore nie in isolasie gesien kan word nie aangesien die sterkte van al die faktore afhanklik is van die aantal vingerlasse in die element. Die verlies aan sterkte as gevolg van elk van die faktore word vergelyk met resultate wat deur ander verkry is en die verskille tussen die resultate word verduidelik. Voorstelle aangaande veranderings aan die Suid-Afrikaanse houtkode is ingesluit en voorstelle vir verdere navorsingsprojekte word gemaak.

SUMMARY

The strength prediction of laminated finger jointed *Eucalyptus grandis* members using computer simulation.

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After discussing the shortcomings of available strength data on South African *Eucalyptus grandis* the author suggests possible research areas so that greater clarity about the strength properties of the abovementioned material can be obtained. Greater clarity about strength properties of the *Eucalyptus grandis* would lead to a better understanding of the failure mechanisms of laminated *Eucalyptus grandis* members. The strength properties of the material and the possible correlation between these properties are required for the simulation of the laminated member's strength.

Various laboratory tests were used to determine the strength properties of the E. grandis and these are discussed, the data are presented and conclusions about the strength properties such as modulus of elasticity, tensile strength parallel to the grain, tensile strength perpendicular to the grain and shear strength are made. The significance of the strength properties with regard to the failure of laminated finger jointed members is discussed. The correlation between the various strength properties, which is used in the simulation of laminated members, is determined. Possible further tests as well as testing methods are suggested.

The simulation method is discussed and a method of simulating random finger joint strength, board strength and board stiffness is presented. This method is expanded to simulate correlated finger joint strength, board strength and board stiffness.

The simulation method is used to simulate tension members that consist of single finger jointed boards. The number of finger joints in the tension member is varied and conclusions are drawn about the effect of such finger joints on the strength of the tension member. This simulation method is then applied to two laminate tension members and conclusions are made about the loss in strength of members due to the number of finger joints in the member.

A simulation method is described and used to determine the possible weakening effect of such factors as the length, depth and type of loading on the strength of laminated finger jointed flexural members. It is pointed out that these factors cannot be seen in isolation as the strength of each factor is affected by the number of finger joints in the member. The loss in strength due to each of the factors described above is compared to results obtained by others and the differences between the results are explained. Recommendations about changes to the South African timber design code are included and suggestions for further research projects are made.

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THE PREDICTION OF LAMINATED EUCALYPTUS GRANDIS MEMBER STRENGTH USING COMPUTER SIMULATION

1.1 INTRODUCTION

Southern Africa has not been blessed with vast forests nor with indigenous trees that provide material suitable for timber construction. The timber from indigenous trees is more suitable for use in the manufacture of expensive furniture or other high quality timber products. As an alternative to imported timber, the softwood and hardwood forests were planted in Southern Africa during the depression of the 1930's.

The softwoods are of the *Pinus patula, P. taeda, P. elliottii, P. pinaster* species and are all marketed under the common name of S A Pine. Only a small percentage of the pine plantations are managed on a 20-30 years rotation for sawlog production. The sawlogs obtained from these plantations are fairly small in diameter. Boards that can be sawn from these sawlogs are limited to maximum cross-sectional dimensions of 75 x 220 mm.

The hardwoods planted for the construction, mining and pulping industry are mainly *Eucalyptus grandis* and *E. saligna*. Most of this timber is grown on a relatively short 12-15 year rotation with the result that sawlogs obtained from these trees are fairly small in diameter. Only about 10% of the total area planted under *E. grandis* is managed on a 20-25 years rotation for sawlog production. Furthermore, the sawlogs obtained from the *Eucalyptus* species are inclined to suffer from growth-stress induced end splitting. The boards that can be sawn from these sawlogs are limited to maximum cross-sectional dimensions of 200 x 35 mm and lengths of 4 m.

Bigger cross-sectional members are supplied by the laminating industry in two ways:

a) They provide laminated pine in stock sizes which augment the limited sawn timber sizes.

b) They provide high grade pine and *E. grandis/saligna* beams in special sizes and for special applications.

In most cases the larger dimensioned timber beams are thus laminated beams. In order to manufacture long beams it is necessary to end joint the boards of a laminate and this is effected by using finger joints. A finger joint profile is sawn at the end of each board, an adhesive is applied and the merging fingers are then joined under pressure. Although finger joints have been manufactured and used successfully for more than 25 years there is some doubt as to their strength in high grade or high density timber. There is considerable evidence that in higher grade or density timber finger joints are weaker than the natural strength reducing features, such as knots, that are permitted by the grading rules.

1.2 MOTIVATION FOR ESTIMATING BEAM STRENGTH

Very high permissible flexural stress values were given for South African hardwood, e.g. *Saligna/E. grandis*, beams in the past. These values were reduced from a highest permissible stress of 23,7 MPa in 1969 to 9,9 MPa in 1980. Tests done at the University of Pretoria on a limited number of beams have shown that the permissible stress could be even lower than 9,9 MPa. Table 1.1 shows how the permissible flexural stresses have declined.

Information source	Permissible stress MPa	Modulus of elasticity MPa
SABS 876-1976[1.11]	15,4 to 23,7	13500 to 17500
MULLER, C/HOUT 61[1.7]	12,4	13800
MULLER, C/HOUT 62[1.8]	12,4	13100
SABS 0163-1980[1.10]	9,9	13100
GRUNOW M N - 1985[1.4]	8,8	14400

TABLE 1.1 Change in permissible flexural stress of laminated *E. grandis* beams.

The dramatic changes in permissible flexural stress caused concern amongst some members of the hardwood laminating industry. These members were interested in ascertaining the true strength of *E. grandis*, whether there has been a decline in the strength and whether some method of improving and predicting the strength of their products could be found.

The flexural stress gradient in solid timber beams determines the bending strength of a timber beam. The steeper the stress gradient is the higher the modulus of rupture becomes. This can be seen when the modulus of rupture for boards tested on flat is compared to that of similar boards tested on edge. This phenomenon gave rise to the adjustments that are made to the permissible bending stress for deep beams and is normally called the depth factor. See for example the British and Australian codes (CP 112, 1971[1.3] and AS 1720-1975[1.1]). Research done by Madsen and

Buchanan[1.5] has confirmed this and they have explained it on the basis of fracture mechanics. Further tests done by Madsen *et al*[1.5] have shown that other effects such as the loading pattern, length of the member and width of the member are also very important.

The tests done by Madsen *et al*[1.5] were limited in that the larger sections were not tested. Stress reduction factors were proposed for the larger sections and for the different loading patterns. (See Figure 1.1) Although the author agrees that the loading pattern is important and could be applied to laminated timber it was felt that the width and depth effect may not necessarily be applicable to South African laminated *E. grandis* timber.

Moody *et al*[1.6] used a large sample of test data to calibrate the following size effect formula used by the ASTM D 07.02.02 task committee:

$$R = R_0 K \left(\frac{d_0}{d}\right)^{1/x} \left(\frac{l_0}{l}\right)^{1/y} \left(\frac{w_0}{w}\right)^{1/z}$$

Where: R is the strength of the beam with dimensions d, l, w;
R_0 is the strength of the standard beam of dimensions d_0, l_0, w_0;
K is the factor that indicates the type of loading;
d_0, l_0, w_0 are the dimensions of the standard beam;
d, l, w are the dimensions of the beam under consideration;
x, y, z are the exponents that were to be determined.

The formula worked very well for the data that Moody *et al* had at their disposal and could have been used on South African laminated timber, if enough data had been available. Although, the formula is ideal as it contains all the volume effects and makes provision for a loading effect, the available test data on South African laminated *E. grandis* beams are so limited that very little statistical significance could be attached to values for *x*, *y*, and *z* that could be obtained by the data. Even with the vast data at their disposal, Moody *et al* felt that a further series of tests was necessary to confirm the values of the exponents x, y, and z that they had obtained.

This formula has a further disadvantage in that changes in the quality of the joints or timber would necessitate a further series of tests to ascertain the exponents, *x*, *y*, *z*, used in the formula. Designers should be aware of the volume and loading effect and have a volume effect formula at their disposal so that realistic member sizes can be calculated. Manufacturers of laminated beams should be given the tools with which they could calculate the statistical distribution of the strength of their products based on the strength distribution of the tensile members that make up the laminated beams. This would allow the manufacturer, who uses sorted or graded timber, to calculate the strength of his laminated beams, to proof load them and hopefully be more competitive.

Tests done at the University of Pretoria, on laminated *E. grandis* beams, having cross sectional dimensions of 50 x 220 mm, have shown that the largest portion of these beams fail in the finger joints of the tension laminates. Failure is initiated when the outer fibres of the finger joint reach the failure stress of the finger joint in pure tension. (see Table 7.1) The stress path changes around the failed finger joint causing principal tensile stresses. This causes delamination of the outer laminate with failure spreading to finger joints in adjacent laminates.

Laboratory tests to test for the length, width, loading and depth effects would be very costly as the number of finger joints in the length of a laminate would depend on the length of available boards and the number of finger joints in the depth would depend on the depth of the beam. To test for the different configurations of length of board and depth of beam would require a vast number of beams. An alternative method was sought which could be used to simulate all these effects so that only a limited number of tests would be required to confirm the method. The usage of the method should be such that it could be used by manufacturers and the method should be flexible enough to be used to design beams using different grades of laminates.

1.3 TEST INFORMATION REQUIRED TO SIMULATE BEAM BEHAVIOUR.

A laminated beam is a number of boards, each having its own average stiffness, that are connected by means of finger joints in the length of the laminate and by a glueline in the depth of the beam. A positive correlation between the strength of the finger joint and the stiffness of either of the two boards that it is connecting may exist.

In order to have a better understanding of the properties and failure mechanism of a laminated beam it is necessary to have the following information about the properties of the elements that make up the beam:

a) The statistical distribution of the average tensile or flexural stiffness of the timber boards that make up the laminates of the beam.

b) The statistical distribution of the tensile strength of the timber and the correlation between tensile or flexural stiffness and tensile strength of the timber.

c) The statistical distribution of the tensile strength of the finger joints and the correlation between the tensile or flexural stiffness of the timber and the tensile strength of the finger joint.

d) The statistical distribution of the length of the timber.

It was assumed that the flexural modulus of elasticity and the tensile modulus of elasticity of *E. grandis* would have a very similar distribution and that the correlation between these two moduli would be very high. The flexural modulus of elasticity is much easier to measure than the tensile modulus of elasticity as the clamps required to exert tensile forces often slip. It is accepted practice in South Africa to grade pine according to the flexural modulus of elasticity, due to the good correlation between the flexural modulus of elasticity and the strength properties. For this reason it was decided to determine the average flexural modulus of elasticity of the *E. grandis* boards and to assume a similar distribution for the tensile modulus of elasticity as the shape of the distribution is more important than the actual value.

1.4 MOTIVATION FOR TENSILE STRENGTH GRADING OF *E. GRANDIS*.

Pine has been successfully mechanically graded in South Africa for a number of years. The good correlation between the flexural stiffness, measured on flat, of boards and the other strength properties makes it possible to use the stiffness as a strength predictor. Central point loading is applied to the boards over a span of 900 mm. The defects in the board are placed under the central point load and the average modulus of elasticity for the 900 mm length determined. This operation is repeated for all the defects in the board and the lowest modulus of elasticity determines the grade stresses.

Laminated *E. grandis* beams are presently manufactured from randomly selected relatively ungraded boards. At most, only the larger strength reducing features, such as large knots, are removed. To obtain the required lengths of board for the manufacture of laminated beams, the boards are end jointed by means of finger joints. The long boards are then glued on top of one another until the required depth of beam is obtained.

The flexural strength of a timber beam is governed by the tensile strength of its outer fibres and the top to bottom stress distribution. The shallower the beam the higher the modulus of rupture of the beam for a given material grade. This is sometimes called the depth effect.(See Australian and British design codes.) Tests done at the University of

Pretoria (Burdzik *et al*[1.2]) indicate that the strength of laminated *E. grandis* beams with depths in excess of 200 mm is governed by the tensile strength of the tension laminates.

The strength of the tension laminates depends not only on the strength of the timber but also on the strength of the finger joints. The finger joints are generally the weak link in the *E. grandis* laminate and especially if they are used in low grade timber (Van Rensburg *et al*[1.13]). The strength of a laminated beam can be greatly reduced if a weak board is used as an outer tension laminate. The stronger boards need to be identified so that they can be used in the outer laminates of beams. Very high density *E. grandis* also needs to be identified as finger joints in very high density timber, glued with phenol resorcinol formaldehyde, which is the adhesive most commonly used for this purpose in Southern Africa, seem to be weaker, based on the fifth percentile strength, than in the lower density timber (Van Rensburg *et al*[1.13]). The fifth percentile strength is important as permissible stresses for timber, in Southern Africa, are obtained by dividing the fifth percentile strength by a factor of safety of 2,22. (Simon[1.9], SABS 0163[1.10])

As *E. grandis* boards are used in laminated beams and as the tension laminates of such beams are critical, it seemed most logical to develop a tensile stress grading system. The grading system for *E. grandis* should preferably be based on the method used to grade pine and use the same mechanical grader, as this method is used in most laminating factories and is understood by the staff. Although more sophisticated methods of grading are available it was felt that this method, however primitive, would enable the saw mills to extract the stronger timber. It would also enable them to use in-grade testing or proof loading to verify the assumed permissible stresses and if necessary adjust them accordingly.

1.5 SHEAR STRENGTH AND TENSILE STRENGTH VERTICAL TO GRAIN.

Failure of an outer tension laminate of a beam, that is subjected to moment loading, at a finger joint or other strength reducing feature would cause changes in the path of the stress lines leading to tensile stress vertical to the grain and horizontal shear stress. Failure of the interface due to the tensile stress vertical to the grain or horizontal shear stress would lead to delamination of the outer laminate, thus resulting in a shallower beam that would then be subjected to the full moment loading. The horizontal shear strength and the tensile strength vertical to the grain are thus most important in containing the total failure of the beam when a defect or finger joint fails in the outer laminate of a beam. If either or both of these strengths is very low delamination of the outer laminate will occur.

It is well known that timber has low strength in resisting forces vertical to the grain. However, very little information is available about the strength of South African *E. grandis* when subjected to these or shear forces.

The author felt, based on the observation of failures in laminated beams of varying sizes, that the tensile strength vertical to the grain and shear strength of *E. grandis* is very low. Delamination would occur in the case of outer tensile laminate failure. However, failure of an inner laminate would not necessarily cause the beam to fail as stress transfer around the failed joint or defect would be through horizontal sliding shear.

The author felt that it was necessary to ascertain whether the tensile strength vertical to the grain was as low as suspected and what the value and distribution of the shear strength was as these strengths would affect the simulation model.

1.6 SCOPE OF RESEARCH.

In order to consider all the pertinent factors affecting the strength of a beam it was necessary to perform the following experimental work and to consolidate available data before attempting a computer simulation to predict the strength of laminated beams and tension members.

a) Tensile tests were performed on full sized randomly selected tension members of as large a population as possible to determine whether it would be possible to grade boards according to strength and also to determine the distribution of strength and modulus of elasticity for bending on flat, using the S A Pine Trugrader. It must be borne in mind that the method used had to be simple as it was to be used in the production line of a laminating factory. More sophisticated grading methods, such as sonic emission and capacitance measurement, were considered but were rejected due to the high level of technical skill required of the operator.

b) Shear and tension vertical to the grain tests were performed on small samples to determine the distribution of these strengths and to see whether there is any correlation between these strengths and flexural modulus of elasticity for bending on flat.

c) Strength data pertaining to finger joints had to be collated and processed to determine the strength distribution.

Taking into consideration the abovementioned factors it was deemed necessary to subdivide the project into the following major compartments:

i) Tensile stress grading of *E. grandis* for loading parallel to the grain.

ii) Tensile stress grading of *E. grandis* for loading perpendicular to the grain.

iii) Shear stress grading of *E. grandis* for loading parallel to the grain.

iv) Consolidation of available strength data for finger joints.

v) Computer model simulation for predicting the strength of laminated tension members.

vi) Computer model simulation for predicting the strength of laminated beams.

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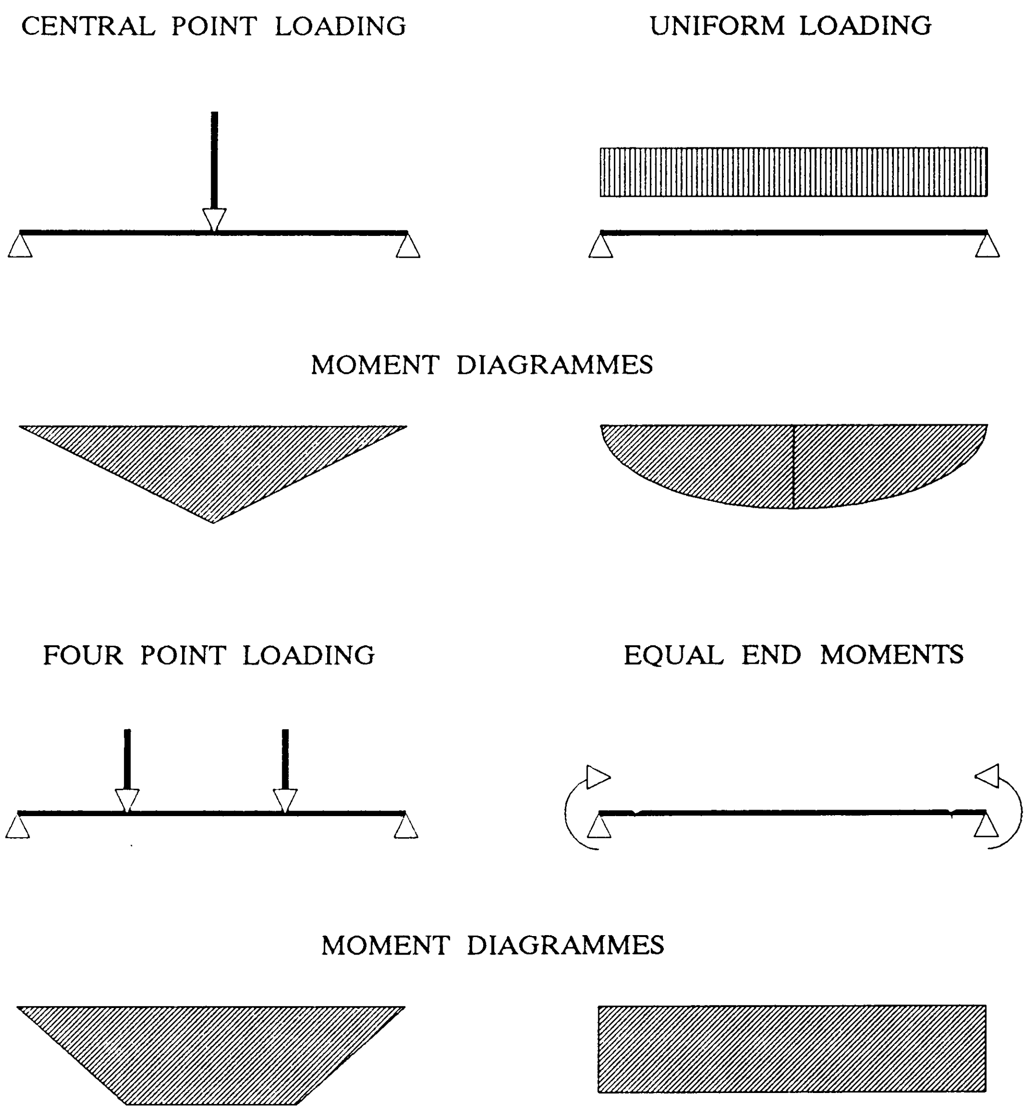

FIGURE 1.1: TYPES OF LOADING

2. PROPERTIES OF *E. GRANDIS* AND TENSILE STRESS GRADING.

2.1 INTRODUCTION.

Vinopal *et al*[2.6] have shown that a good correlation exists between the flexural strength of South African pine and its flexural modulus of elasticity for bending on flat. A "localized" stiffness of the boards is determined by placing defects in the centre of a 900 mm span and measuring the deflection of the board under a predetermined three point loading. A defect is any knot, slope of grain or other distortion of the grain. The lowest "localized" modulus of elasticity is used as a predictor of the flexural strength and other strength properties of the member.

Very little recent information about the strength properties of full sized *E. grandis* boards from 25 year old and older trees is available. Tests to determine the strength properties of boards from twelve year old *E. grandis* trees were evaluated by Bronkhorst *et al*[2.1] and they came to the conclusion that the correlation between flexural stiffness for bending on flat and bending strength was too low for flexural stiffness to be used as a strength predictor for the material tested. They felt that timber obtained from older trees might show a better correlation between the strength properties and the flexural modulus of elasticity for bending on flat.

Laboratory tests on *E. grandis* boards, from 25 year and older trees, by van Rensburg *et al*[2.5] have shown that there is a very good correlation between tensile strength of a visually clear, 22,5 x 30 x 420 mm long specimen, and its density. The correlation coefficient between density and tensile strength for these visually clear *E. grandis* specimens was found to be 0,76. The plot of the simple linear regression line of tensile strength versus density showed a strong upward trend. It was, however, assumed that results obtained from this specimen size would not necessarily apply to full sized members.

Bearing the above-mentioned in mind, it was felt that a tensile stress grading method, based on the methods used for South African pine, may be possible. The grading system should use the correlation between any property based on some non-destructive test and the tensile strength. Properties that were considered were density, modulus of elasticity and colour. Colour was considered as there had been suggestions from sources in the industry that a good correlation between colour intensity and density existed with the darker material being more dense than the lighter material. These properties could be combined to find a stress grading method for tensile strength with a high correlation coefficient. It was felt that to obtain statistically significant figures a random sample of boards of as large a population as possible had to be tested for tensile strength and the other properties mentioned.

Important data that could be obtained from a series of tests on *E. grandis* boards could be the statistical distribution of density, tensile strength and the modulus of elasticity.

2.2 EXPERIMENTAL PROCEDURE.

A total of 520 random specimens from different plantations and from different aged trees, measuring 85 mm by 30 mm of varying length, were chosen out of a very large population from the Politsi area of the Eastern Transvaal. None of the boards was graded in any way no matter how big the defect or how low the density of the timber. These were planed to the standard width of 75 mm and a thickness of 25 mm.

The specimens were visually divided into eight colour groupings, from light in colour to dark in colour, as there had been suggestions that the lighter timber was less dense than the darker timber. Van Rensburg *et al*[2.5] had found a fairly good correlation between density and tensile strength and it was hoped that some correlation between tensile strength and colour existed. Sorting by colour would be an inexpensive grading method and could be done electronically on a continuous production line.

The dimensions and mass of all the samples were measured and knots were identified, marked and the size noted. Other strength reducing features such as slope of grain were neglected as difficulty was found, by the unskilled labour, in determining this. The boards were placed in a stress grader that was developed for the grading of South African pine by the Council for Scientific and Industrial Research in South Africa. Centre point loading over a span of 900 mm was applied to the boards on flat to obtain the average flexural modulus of elasticity. To allow for distortion of the boards or overhang, a preload of 200 N was applied. Each of the marked defects was placed under or as close to the loading position as possible so that the "local" modulus of elasticity could be determined. The loading was increased by a calibrated 500 N load and the increase in deflection was measured with a dial gauge.

Shear deflection was ignored in the calculation of the modulus of elasticity as this is very small when compared to to the bending deflection for the span to depth ratio under consideration.

Bending deflection of beam with point load in the centre of the span	Deflection	=	$\frac{W\ L^3}{48}$
		=	5,8 mm (for loading used)
Shear deflection of same beam	Deflection	=	$\frac{1{,}5 \times W\ L}{4\ G\ A}$
		=	0,07 mm (for loading used)

The moisture content of a random sampling of the specimens was determined with an electronic moisture meter.

The failure strength of all the specimens was determined in a horizontal tensile testing rig developed by the Council for Scientific and Industrial Research in South Africa. Transverse forces are applied hydraulically to high friction rubber grips on either side of the ends of the board, which is then held in position. One of the grips is fixed while the other applies a longitudinal tensile force to the specimen. The rubber grips do no visible damage to the specimen but do, however, need a gripping length of about 400 mm which results in long tensile specimens being required.

2.3 EXPERIMENTAL RESULTS.

The majority of the specimens broke at a knot, slope of grain or other defect in the board between the two sets of grips of the tensile testing rig. In a few cases the initiation of the break occurred in the grips and spread to other defects between the grips by means of shear failure. In a very limited number of cases the friction grips could not maintain the load and slipped as a result of the timber specimens having very slippery surfaces. Specimens, where the grips slipped, were discarded.

The moisture content was found to vary very little as the specimens had been conditioned for more than three months to approximately 8 - 10 % equilibrium moisture content.

Figure 2.1 shows the distribution of the tensile strength of the sample and a log-normal curve has been fitted. The data were divided into 27 intervals, normal distribution and log-normal distributions assumed and χ^2 tests, Ang *et al*[2.8], performed. The χ^2 value for the assumed normal distribution was 60,3 and for the assumed log-normal distribution 15,9 thus making the log-normal distribution a better fit. The log-normal distribution is also more suitable for strength simulation methods as assumed normal distribution could give negative strengths. Figure 2.2 shows the distribution of the natural logarithm of the stresses. The average tensile strength was 45,8 MPa with a fifth percentile strength of 18,8 MPa.

Figure 2.3 shows the plot of modulus of elasticity for bending on flat versus tensile strength for all the specimens. A simple linear regression was calculated and the regression line has been plotted. The correlation coefficient between modulus of elasticity and board strength is 0,55 and formula for the regression line is given by the following:

Stress = 3,78 * (modulus of elasticity) - 6,36

Stress in MPa
modulus of elasticity in GPa

Figure 2.4 shows the plot of density versus tensile strength for all specimens. A simple linear regression was calculated and the the regression line has been plotted. The correlation coefficient between density and tensile strength of the boards is 0,076 and formula for the regression line is given by the following:

Stress = 0,014 * density + 42,2

Stress in MPa
density in kg/m^3

Figure 2.5 shows the plot of visual colour grade versus tensile strength. The colours are plotted at discrete intervals as only eight groups were chosen. The correlation coefficient between the visual colour grade and the tensile strength of the boards is very low at 0,0378.

Figure 2.6 shows the plot of knot size versus tensile strength. Timber that failed at sections that appeared to be visually clear were given a defect size of 1 mm. The correlation coefficient between defect size and tensile strength is 0,51 and the formula for the regression line is given by the following:

Stress = -0,96 * defect size + 64,79

Stress in MPa
defect size in mm.

An exponential regression curve fitted through the points has a slightly higher correlation coefficient of 0,53. This is not really a significant improvement and is thus not shown.

The specimens were grouped according to their modulus of elasticity, the fifth percentile value calculated for a confidence level of 0,5 and the permissible stress derived by dividing the fifth percentile strength by 2,22. (SABS 0163[2.4]) The results are shown in Figure 2.7 with the regression line shown for the different values.

2.4 DISCUSSION.

The correlation between modulus of elasticity in bending and tensile strength is not that promising. Although the correlation coefficient is low, the modulus of elasticity in bending could be used as an indicator for the tensile strength of *E. grandis* boards. However, the distribution given in Figure 2.2 gives a fifth percentile strength of 21,40 MPa with the permissible tensile strength being obtained by dividing this value by 2,22. (SABS 0163[2.4]) A permissible tensile strength of 9,64 MPa results. If the correlation between modulus of elasticity and tensile strength (see Figure 2.7) is used to predict the permissible strength of the boards, only boards having a modulus of elasticity higher than 15 GPa would have a predicted strength greater than 9,64 MPa. If the distribution of strength versus modulus of elasticity given in Figure 2.3 is taken into account, it shows that almost half the boards have a modulus of elasticity lower than 15 GPa. It would appear that grading according to modulus of elasticity would not be cost effective.

It must be borne in mind that the boards used were not visually graded at all. The possibility was considered that if the boards with the most obvious strength reducing features were eliminated, as is the case with the stress grading of pine, a better correlation between modulus of elasticity and tensile strength could have been obtained. Timber having a density less than 400 kg/m^3 and knot sizes greater than 20 mm were removed from the data. Figure 2.8 shows that there is no improvement in the correlation between tensile strength and modulus of elasticity as the correlation coefficient was 0,51.

The distribution of the tensile strength of the sorted timber is given in Figure 2.9. It was expected that by removing the larger defects, the mean tensile strength would improve and that the lower strength values would fall away. The distribution shows that this has happened. If a log-normal distribution is assumed, a mean tensile strength of 55,6 MPa with a permissible tensile stress of 11,9 MPa is found. This is a large improvement in the permissible tensile strength and if one bears in mind that 71 % of the specimens fall into this category the improvement is noteworthy.

The timber that falls outside of this sorted group, i.e. timber with defects greater than 26 % of the sectional area, still has a mean tensile strength of 33,43 MPa and a permissible stress of 7,7 MPa. The distribution of the tensile strength of these boards is given in Figure 2.10. This method of sorting the *E. grandis* by defect size is a much more cost effective way than grading by modulus of elasticity.

Stress grading by modulus of elasticity to obtain permissible tensile stresses greater than 11,9 MPa would mean that the boards would require a modulus of elasticity greater than 17 GPa. Only about one third of the boards tested had a modulus of elasticity in excess of 17 GPa.

Tests done earlier (Van Rensburg *et al*[2.5]) on visually clear 22,5 x 30 x 400 mm long *E. grandis* specimens show a good correlation between density and tensile strength. The correlation coefficient for these relatively small specimens was 0,759. However, it was found that for the full sized specimens tested the correlation between density and tensile strength was very weak when compared to that between modulus of elasticity and tensile strength. It is not recommended that density be used as a strength indicator for *E. grandis* boards with defects.

The correlation between visual colour grading and strength is not promising at all.

A combination of visual defect identification and grading according to modulus of elasticity is a possibility. This combination would require a much greater correlation coefficient to make it competitive with the sorting of the timber according to defect size.

Newer methods of stress grading are being investigated with sonic emission, light reflection and capacitance measuring devices showing some promise. These new methods should be borne in mind if further tests are envisaged.

2.5 CONCLUSION.

E. grandis when used in laminated beams is subject to tensile and compressive stresses. In order to use the timber more effectively (Louw[2.2]) it is necessary to grade the timber for tensile strength as this is the critical stress. Methods for the stress grading of unsorted Southern African *E. grandis* were sought, using the relatively unsophisticated simple methods that are used for the grading of South African pine. The usual stiffness versus strength method as well as density and or colour versus strength methods were considered. Of these methods the bending stiffness versus tensile strength method showed the most promise. Preliminary sorting of the timber did not result in a better correlation between tensile strength and bending stiffness. The cost effectiveness of grading by using the correlation between modulus of elasticity and tensile strength is not good. Until a better method of grading can be found the author suggests that the timber be sorted by defect size and that 2 grades could be used, namely 7,7 MPa for timber having defects greater than or equal to 27 % of the cross sectional area and 11,9 MPa for timber with defects less than 27 % of the cross sectional area.

2.6 REFERENCES.

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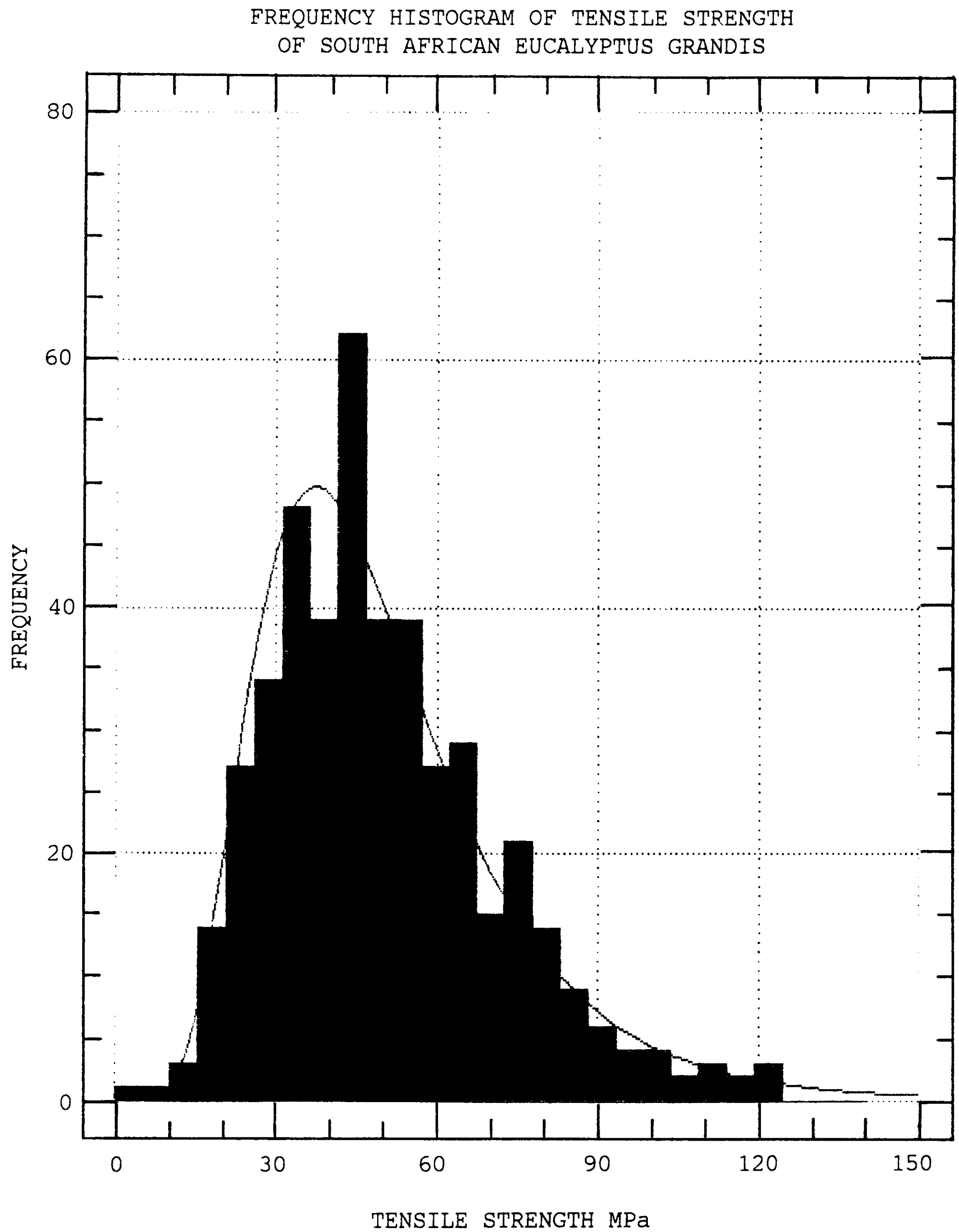

FIGURE 2.1 DISTRIBUTION OF TENSILE STRENGTH OF UNGRADED EUCALYPTUS GRANDIS BOARDS.

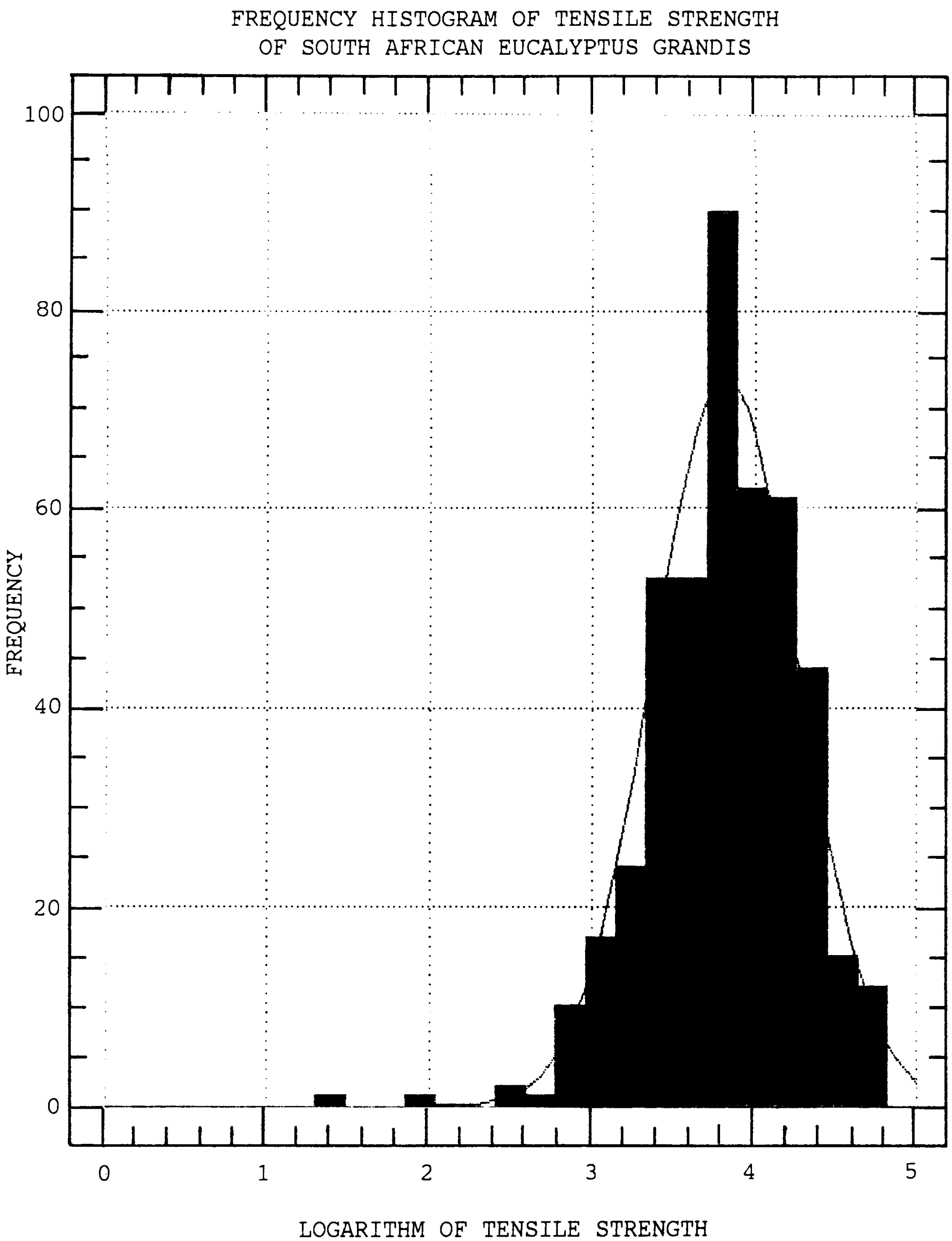

FIGURE 2.2 DISTRIBUTION OF THE NATURAL LOGARITHM OF THE TENSILE STRENGTH OF UNGRADED EUCALYPTUS GRANDIS BOARDS.

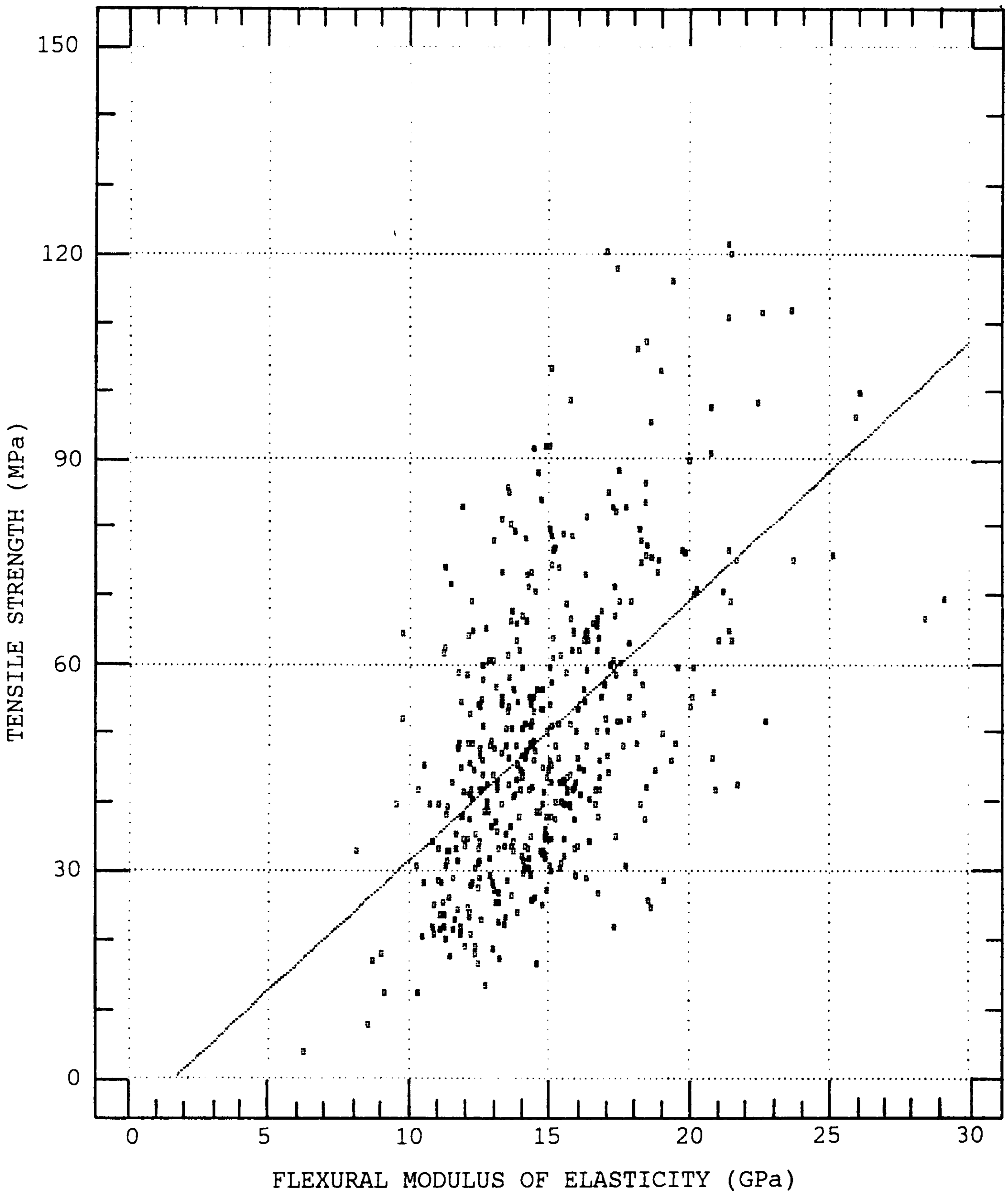

FIGURE 2.3 REGRESSION OF TENSILE STRENGTH VERSUS LOCAL FLEXURAL MODULUS OF ELASTICITY OF UNGRADED EUCALYPTUS GRANDIS BOARDS.

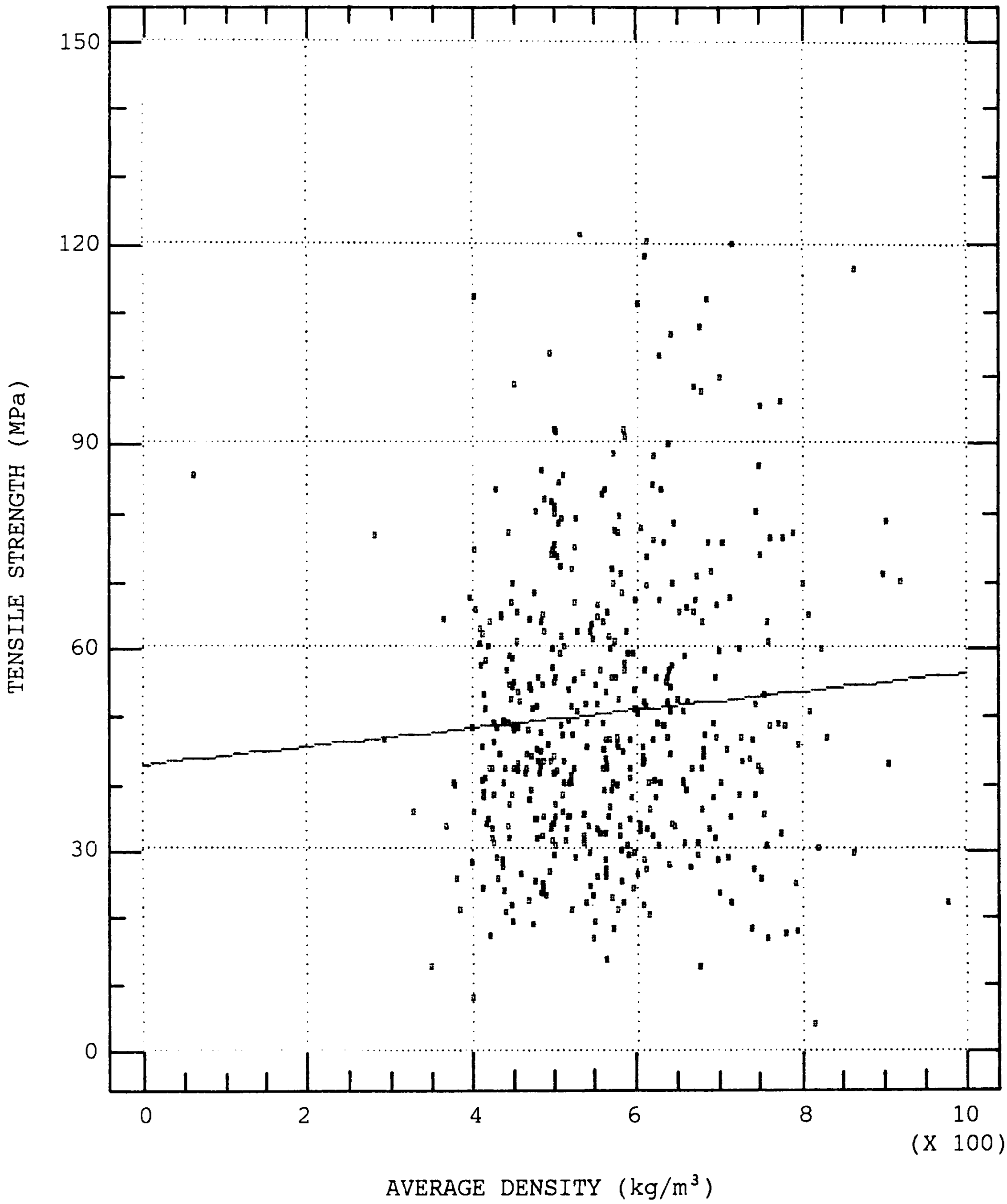

FIGURE 2.4 REGRESSION OF TENSILE STRENGTH VERSUS AVERAGE DENSITY OF EUCALYPTUS GRANDIS BOARDS.

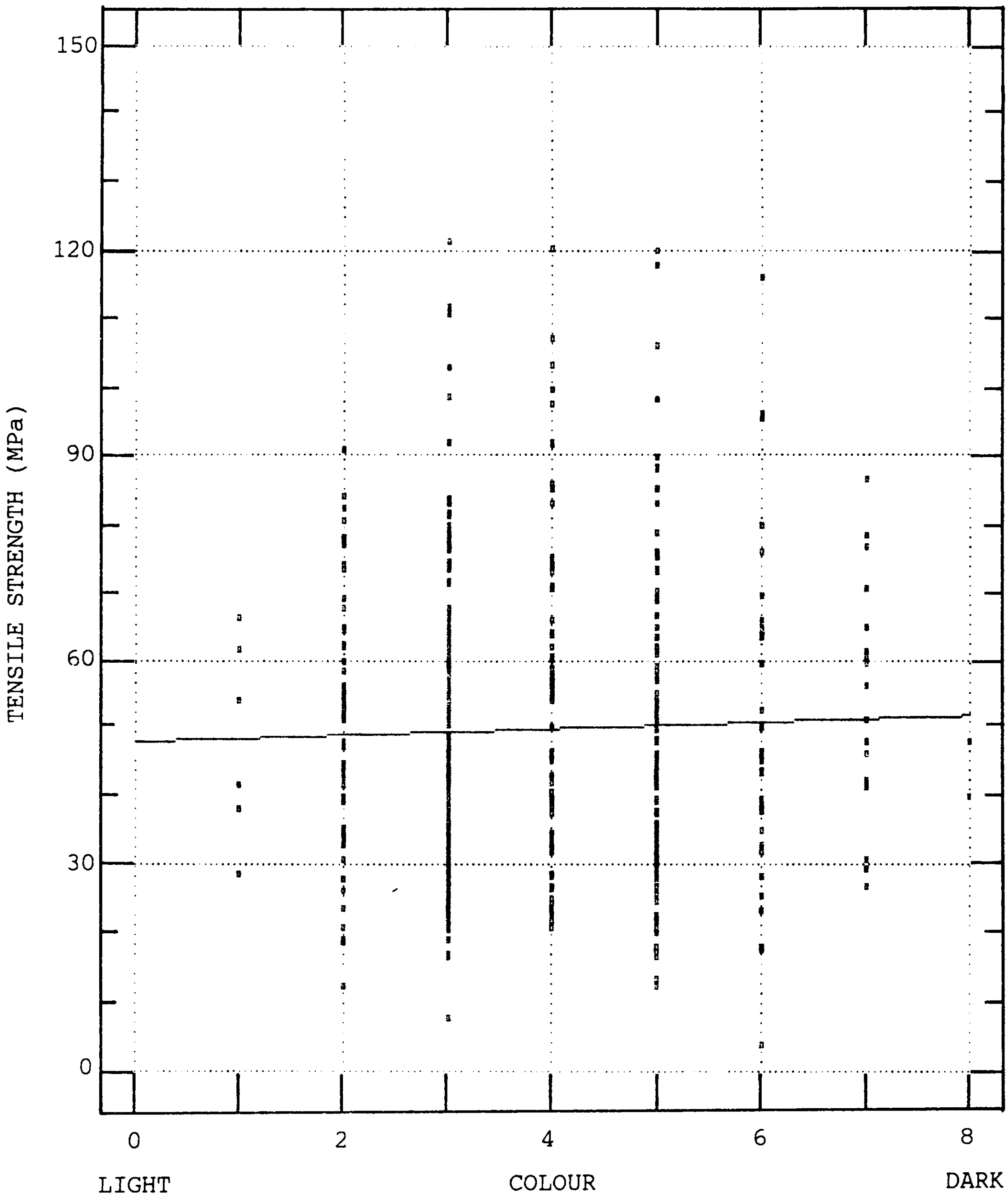

FIGURE 2.5 REGRESSION OF TENSILE STRENGTH VERSUS COLOUR FOR EUCALYPTUS GRANDIS BOARDS.

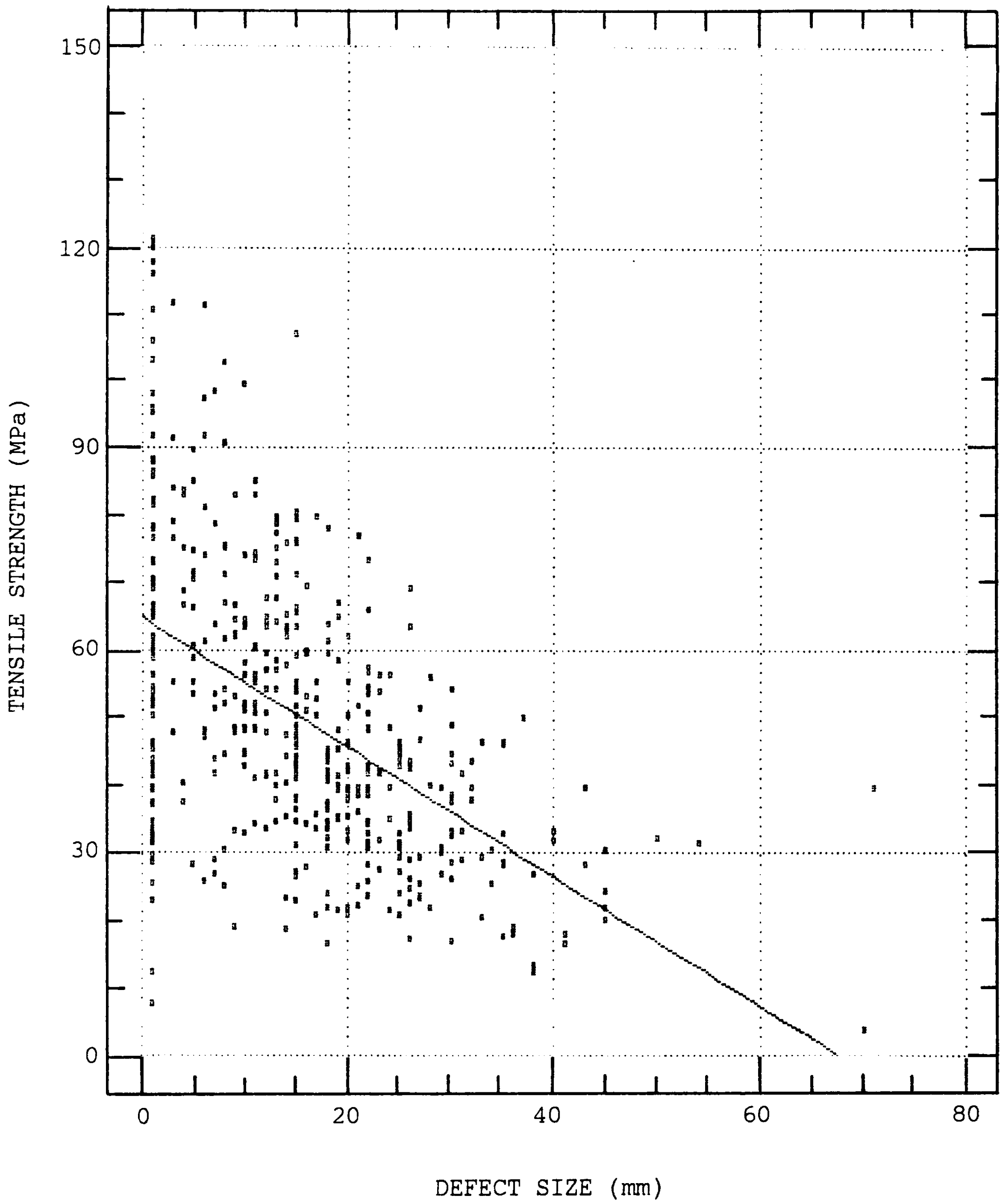

FIGURE 2.6 REGRESSION OF TENSILE STRENGTH VERSUS DEFECT SIZE FOR 75 mm WIDE EUCALYPTUS GRANDIS BOARDS.

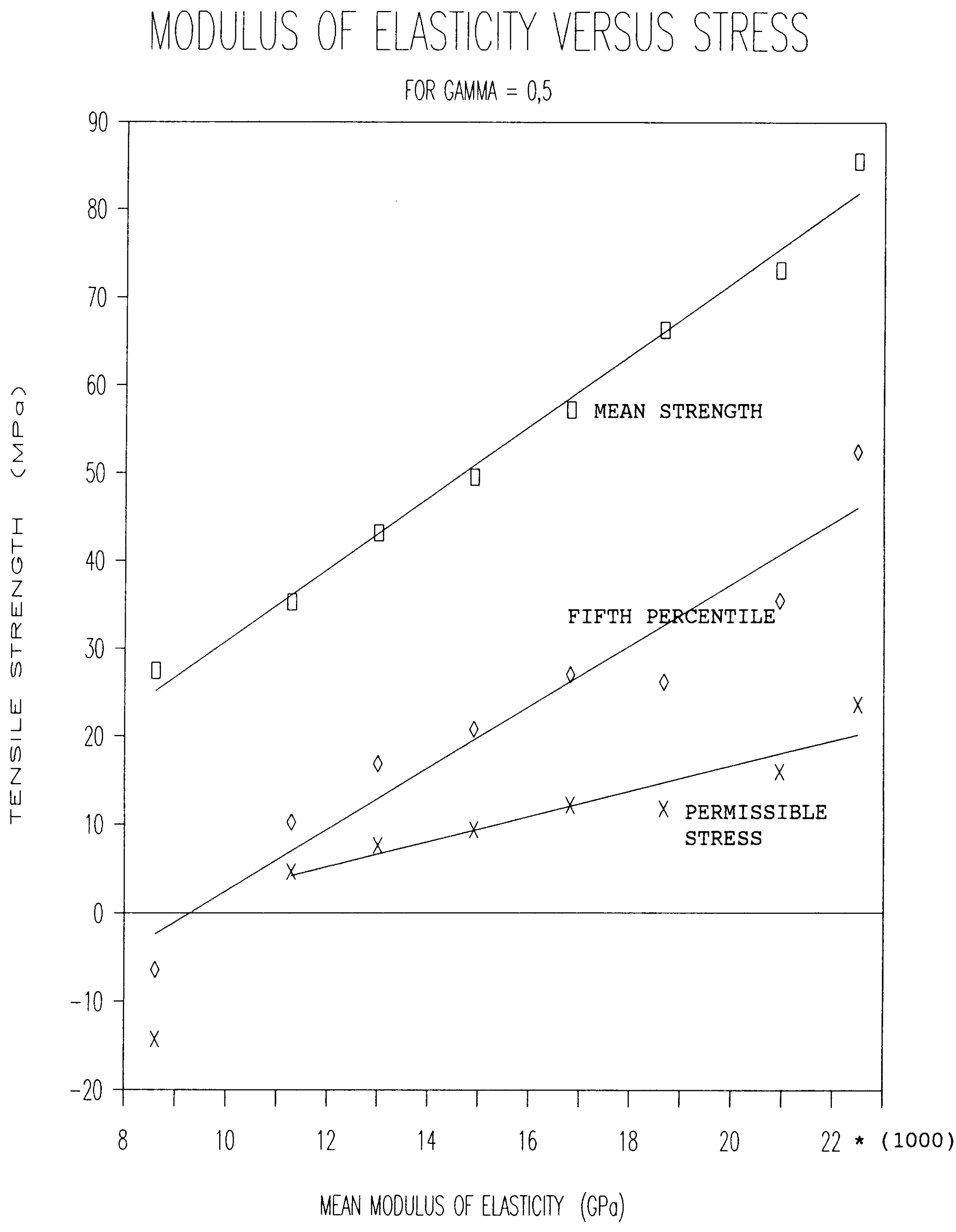

FIGURE 2.7 REGRESSION OF TENSILE STRENGTH VERSUS MODULUS OF ELASTICITY WITH FIFTH PERCENTILE VALUES SHOWN AS WELL AS PERMISSIBLE STRESS.

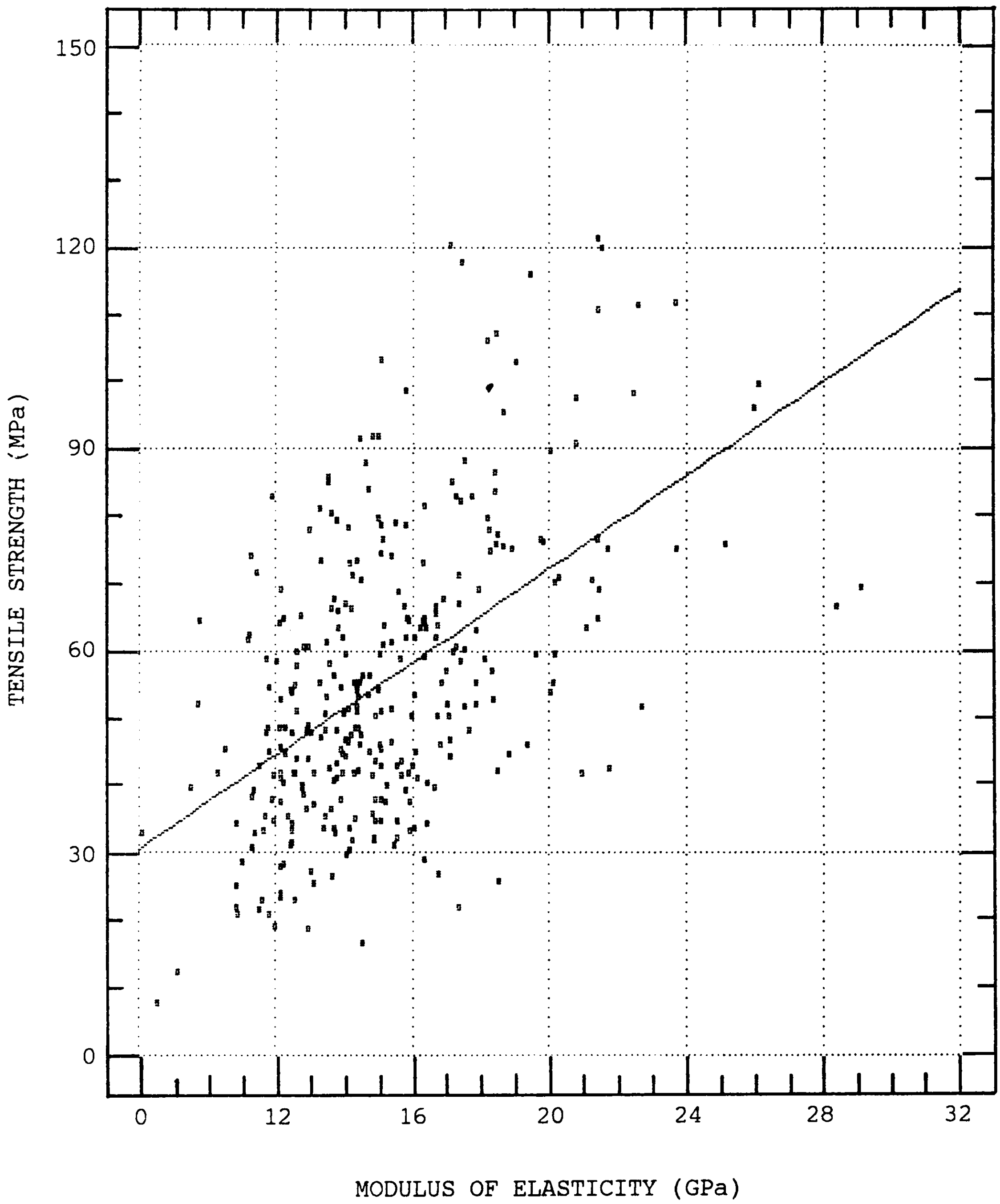

FIGURE 2.8 REGRESSION OF TENSILE STRENGTH VERSUS MODULUS OF ELASTICITY FOR BOARDS HAVING DEFECTS LESS OR EQUAL TO 27% OF THE CROSS SECTIONAL AREA.

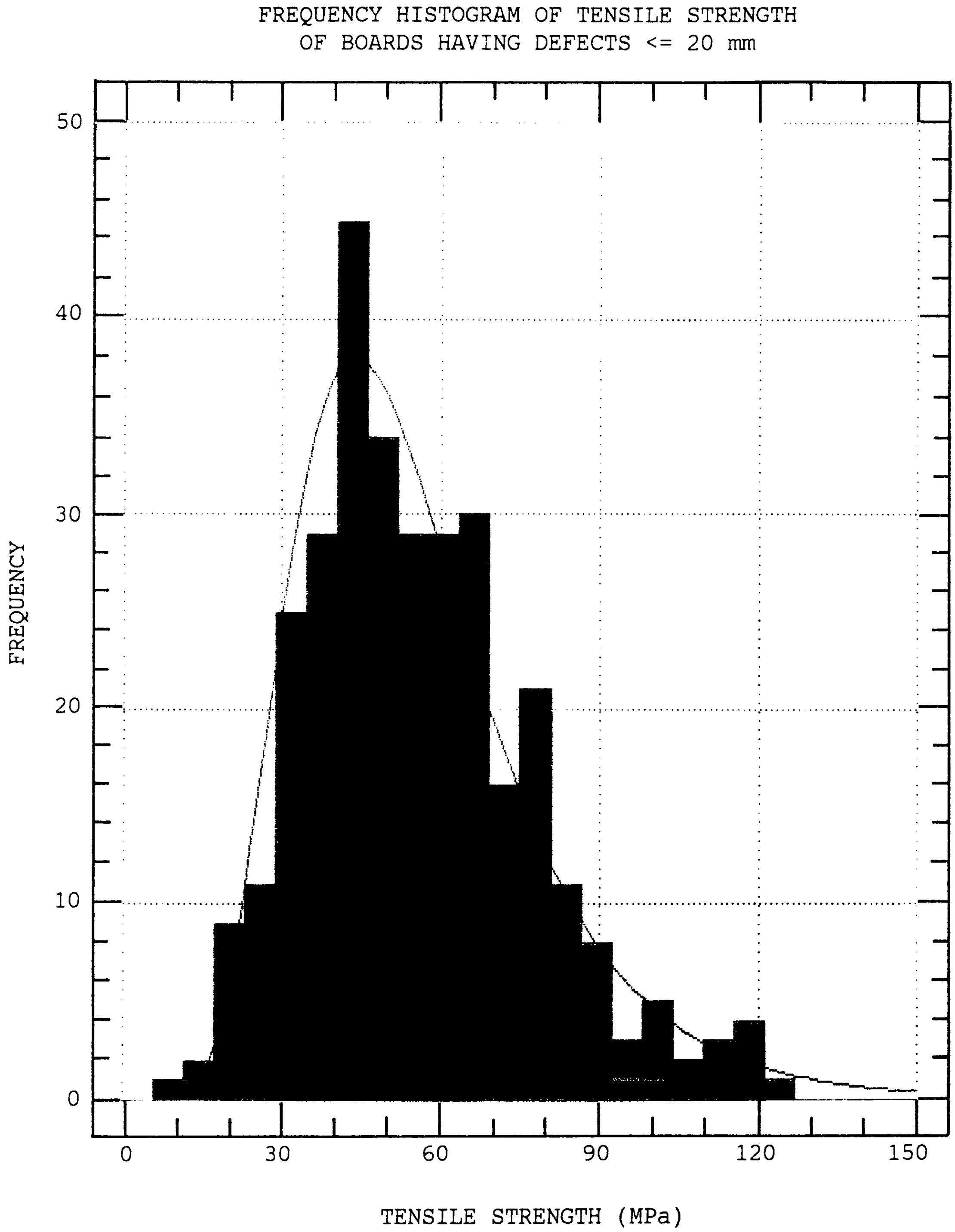

FIGURE 2.9 DISTRIBUTION OF THE TENSILE STRENGTH OF BOARDS HAVING DEFECTS LESS OR EQUAL TO 27% OF THE CROSS SECTIONAL AREA.

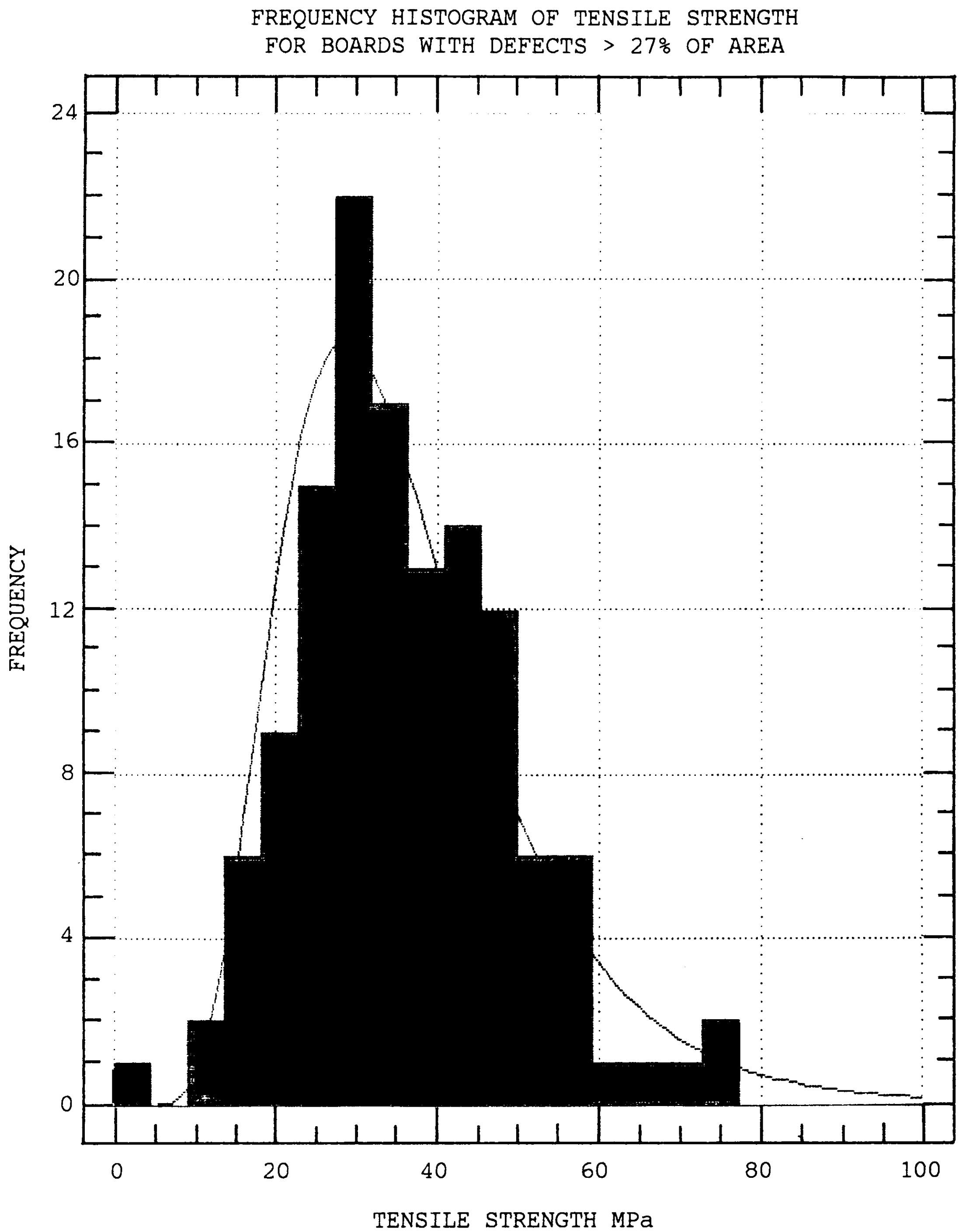

FIGURE 2.10 DISTRIBUTION OF TENSILE STRENGTH OF BOARDS HAVING KNOTS GREATER THAN 27% OF THE CROSS SECTION AREA.

3. TENSILE STRENGTH PERPENDICULAR TO GRAIN.

3.1 INTRODUCTION.

Most laminated South African *E. grandis* beams fail at finger joints in the tension laminates. Delamination of the failed laminates appears to take place with the result that the beams as a whole fail. Delamination or crack propagation will take place if the shear strength or strength perpendicular to the grain is too low to transfer the forces between the failed laminate and its neighbour.

No recent information about the strength perpendicular to the grain of full sized *E. grandis* was available thus making it impossible to ascertain whether delamination was taking place due to this strength property being inadequate. The indications were that the strength would be low and that this low perpendicular to the grain strength would be the major cause of delamination.

3.2 EXPERIMENTAL PROGRAMME.

In order to obtain statistically significant values for the strength perpendicular to the grain, a random sample of 100 *E grandis* boards, measuring 170x30 mm with lengths of up to 1,02 m, was selected from a large population from the Politsi area of the Eastern Transvaal. These specimens were planed to a standard thickness of 25 mm.

The dimensions and mass of each specimen were noted. Central point loading over a span of 600 mm was applied to the boards on flat, to obtain the flexural modulus of elasticity. To allow for distortion of the boards and/or overhang, a preload of 200 N was applied. The loading was increased by a calibrated 1,5 kN load and the increase in deflection was measured with a dial gauge. Shear deflection was ignored in the calculation of the modulus of elasticity as it is small when compared to bending deflection for the span to depth ratio under consideration.

The specimens had been conditioned for more than 3 months to an equilibrium moisture content of approximately 8-10%. The moisture content of a random sampling was determined with an electronic moisture meter and found to be in the region of 10%.

Seventy five millimeter wide strips were cut from each board. The specimens were given a neck area of 20x25 mm as in Figure 3.1. The specimens were tested in a Losenhauser tensile testing rig with the top of the specimen being held in the grip of the machine, while the bottom of the specimen was held by means of a bolted connection. The bolted connection consisted of a single bolt through the specimen so that eccentric loading would be limited. Force was applied to the bolted connection by means of the bottom grip of the testing rig. It was assumed that a certain number of the test specimens would fail due to damage during the manufacture of the specimen while others would fail due to small moments being applied as eccentric loading could be expected if the specimen was not placed correctly in the grips of the testing rig.

3.3 EXPERIMENTAL RESULTS.

All but four of the test specimens failed in the necked area. Two specimens failed at knots in the region of the testing rig grip due to damage done to the timber by the grip. The other two specimens failed at the bolt hole due to a horizontal crack forming and crack propagation taking place. (See Figure 3.2)

A large number of the specimens showed extremely low strength and some of these low strengths were probably due to prior damage of the specimens or eccentric loading being applied to specimens that were not placed correctly in the testing rig. Figure 3.3 shows the frequency distribution of all the values and a two parameter Weibull[3.1] distribution curve has been fitted. Weibull distributions are used in cases where the minima are of importance rather than the means.

Due to the large number of specimens that seemed to have suffered from damage during manufacture and the fact that the frequency distribution of the perpendicular to grain tensile strength did not have the same shape as the frequency distributions for parallel to grain tensile strength or for shear strength, caused concern.(See Figure 2.1 and Figure 4.4) The data was adjusted by removing the extremely low strength values and Figure 3.4 shows the frequency distribution of perpendicular to grain tensile strengths of the remaining data to which a log-normal distribution has been fitted. Figure 3.5 shows the distribution of the natural logarithm of the perpendicular to grain tensile strength and a normal distribution curve has been fitted.

The mean of the natural logarithms of the adjusted experimental results is 0,39 and the standard deviation is 0,44. Using the method described by Simon[3.2] a permissible stress of 0,31 MPa results. The permissible stress given by SABS 0163[3.3] is 0,4 MPa. Although the experimental value for permissible tensile strength perpendicular to the grain is lower than that given by SABS 0163[3.3] the author would not recommend the lowering of the value given in SABS 0163. Uncertainty about prior damage to or eccentric loading of the test specimens, makes further experimental testing a necessity.

Figure 3.6 shows the plot of tensile strength perpendicular to grain versus density for the adjusted experimental results. A linear regression with a correlation coefficient of 0,60 has been plotted. The equation for the regression is given by:

Tensile strength perpendicular to grain = -1,79 + 0,00427 * (Density)

where tensile strength is in MPa
density is in kg/m^3

The correlation coefficient is good enough to be used as a strength predictor in cases where tensile strength perpendicular to the grain is critical. A few of the lower strength values could possibly be eliminated as they appear to fall under the damaged or eccentrically loaded heading.

Figure 3.7 shows the plot of flexural modulus of elasticity versus tensile strength perpendicular to the grain for the adjusted experimental results. A linear regression with a correlation coefficient of 0,19 has been plotted. The correlation between flexural modulus of elasticity and tensile strength is too low to be used as a strength predictor.

3.4 DISCUSSION.

The experimental results were not as reliable as was hoped. Boards that were wide enough to give reasonably sized specimens were difficult to obtain. Specimens were difficult to prepare and damage prior to testing was suspected. The difficulty of applying a non eccentric load cannot be stressed too much and many of the specimen may have been subjected to some sort of moment loading.

Tensile strength perpendicular to the grain can be expected to be between 1/10 and 1/20 of the tensile strength parallel to the grain. The sample that was tested was found to have a mean strength parallel to the grain of 45,8 MPa. The mean tensile strength perpendicular to the grain was found to be 1,47 MPa which is very low. The permissible tensile strength parallel to the grain for the population was estimated at 9,64 MPa and that of permissible tensile stress perpendicular to the grain at 0,32 MPa. The ratio between permissible tensile strength perpendicular to and parallel with the grain is then about 1/30 which seems to be on the low side. Further laboratory tests are required to ascertain the true strength.

Care must be taken with further testing that the specimens are not damaged prior to testing and that no eccentric loading is applied to the test piece. If possible larger specimens and greater accuracy in the measuring of dimensions and loads must be used.

This study is about modelling the behaviour of laminated beams with finger joints and especially finger joints in the tensile zones of the beam. It has been shown that the tensile strength perpendicular to the grain is very low and that this low strength combined with the low shear strength will cause delamination of the outer tensile laminate of a beam when failure of a finger joint occurs in that laminate. A failed finger joint in a beam is equivalent to a butt joint and Leicester[3.4] has shown that the strength of butt joints in laminated beams is a function of the density of the timber. In Chapter 4 it is shown that, even when high density timber is assumed, the butt joint is weak. This confirms the assumption that failure of a finger joint in timber with low perpendicular to grain strength will cause delamination of the failed laminate due to crack propagation.

3.5 REFERENCES.

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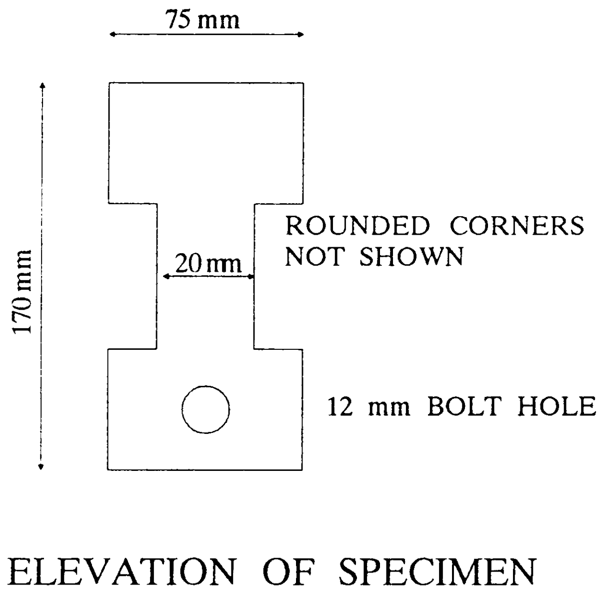
FIGURE 3.1 SPECIMEN SHAPE WITH FORCE APPLICATION SHOWN.



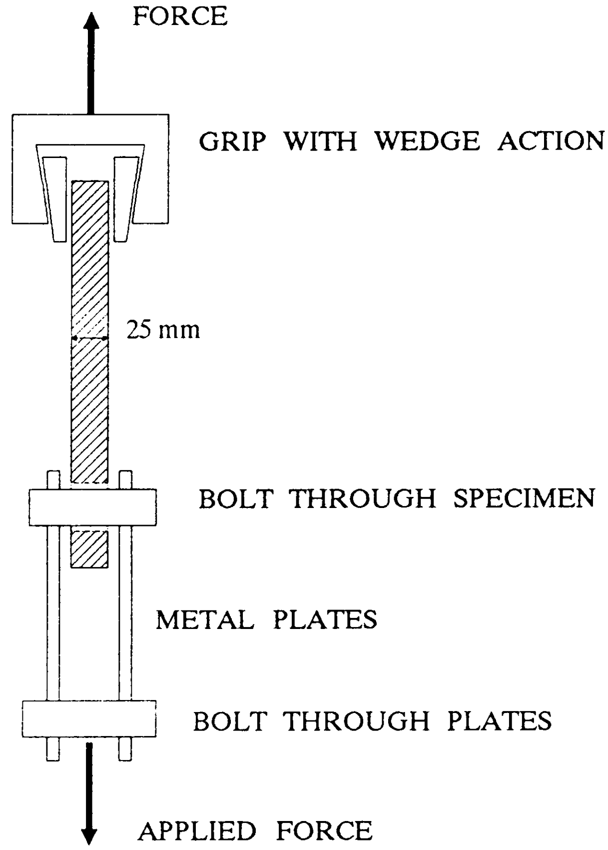
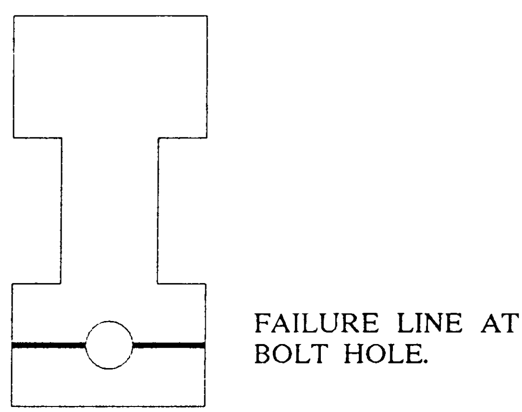


FIGURE 3.2: FAILURE OF SPECIMENS AT BOLT HOLES.



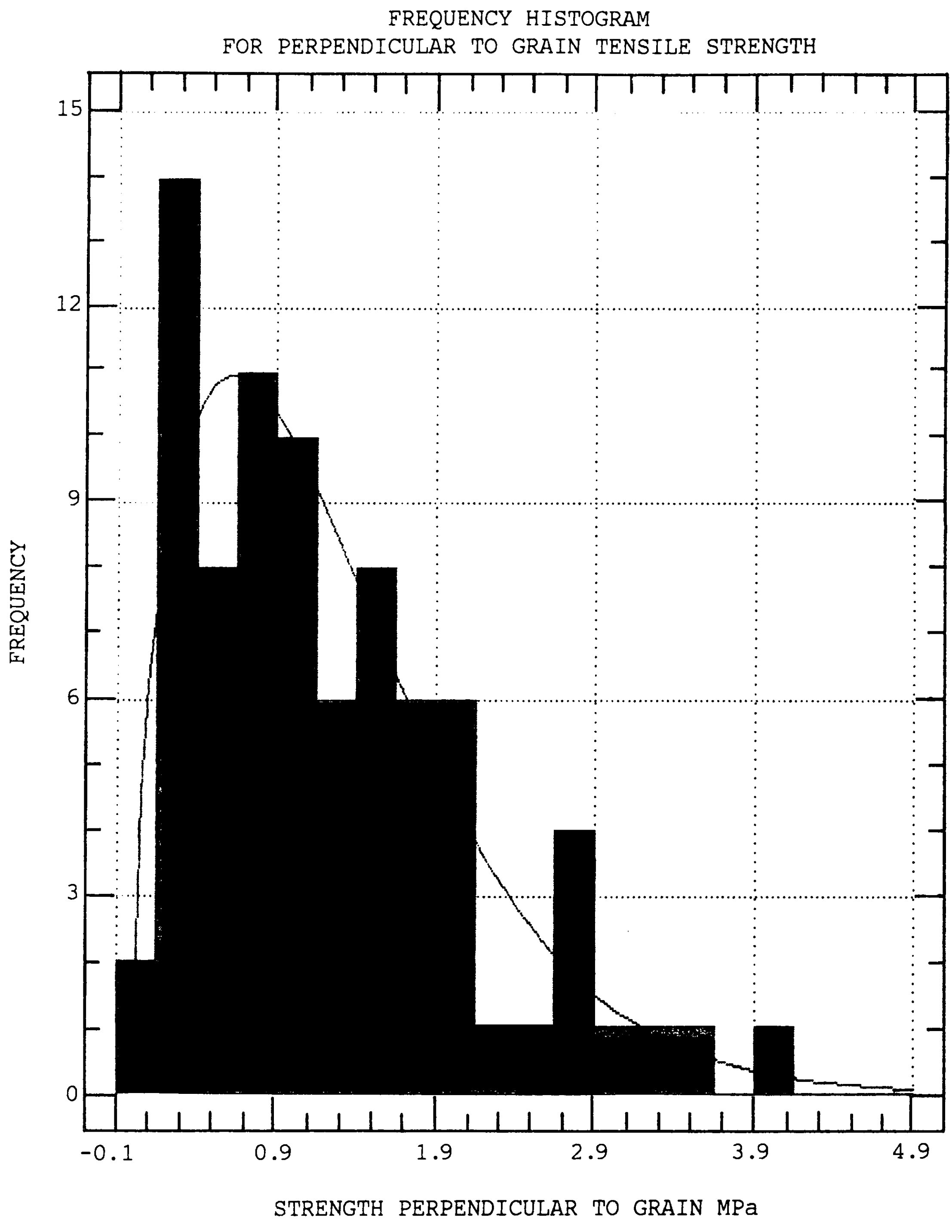


FIGURE 3.3 FREQUENCY DISTRIBUTION OF PERPENDICULAR TO GRAIN TENSILE STRENGTH OF EUCALYPTUS GRANDIS TO WHICH A TWO PARAMETER WEIBULL DISTRIBUTION HAS BEEN FITTED.

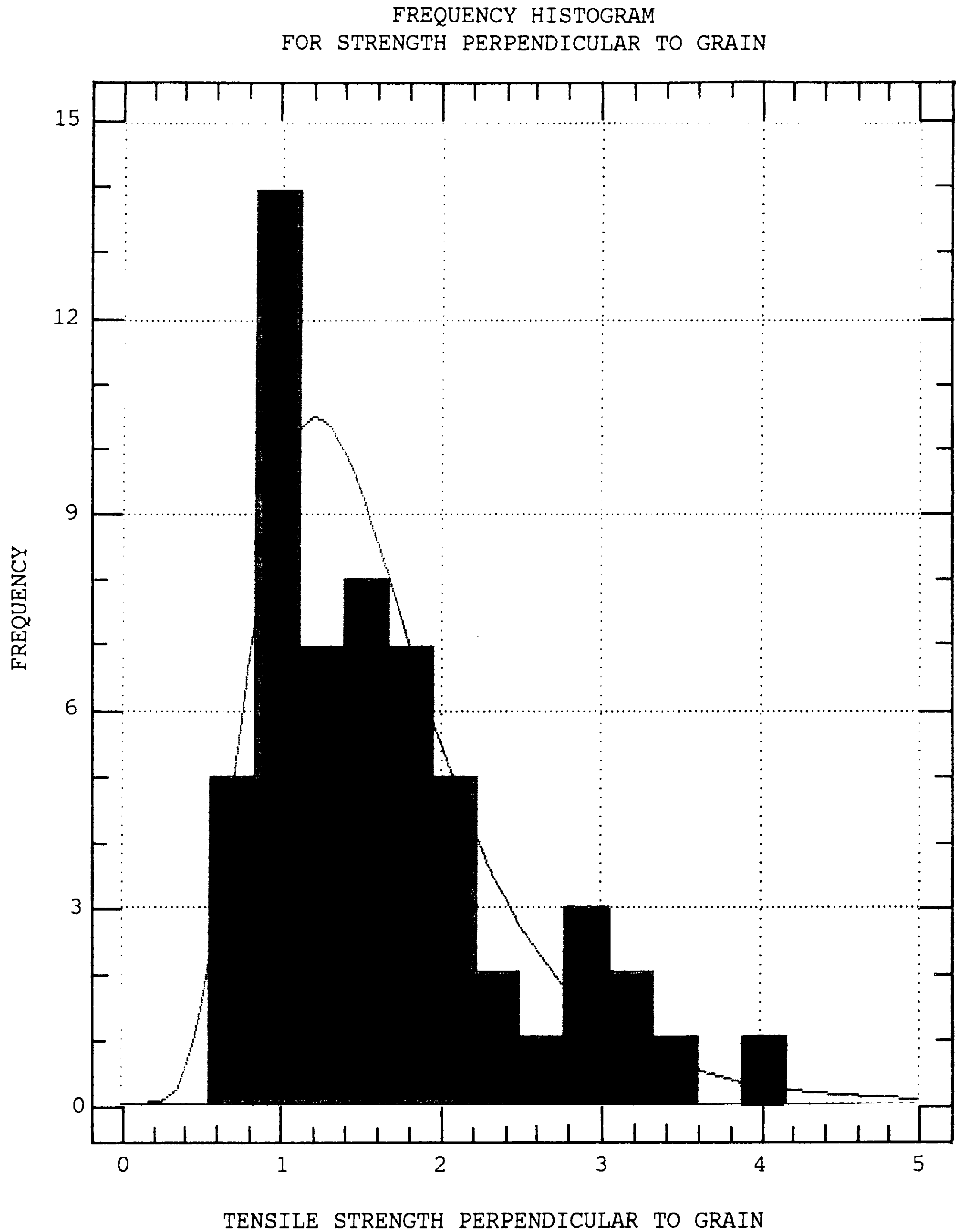


FIGURE 3.4 FREQUENCY DISTRIBUTION OF PERPENDICULAR TO GRAIN TENSILE STRENGTH OF EUCAPYPTUS GRANDIS WITH A FITTED LOG-NORMAL DISTRIBUTION CURVE. LOWER STRENGTH VALUES HAVE BEEN REMOVED.

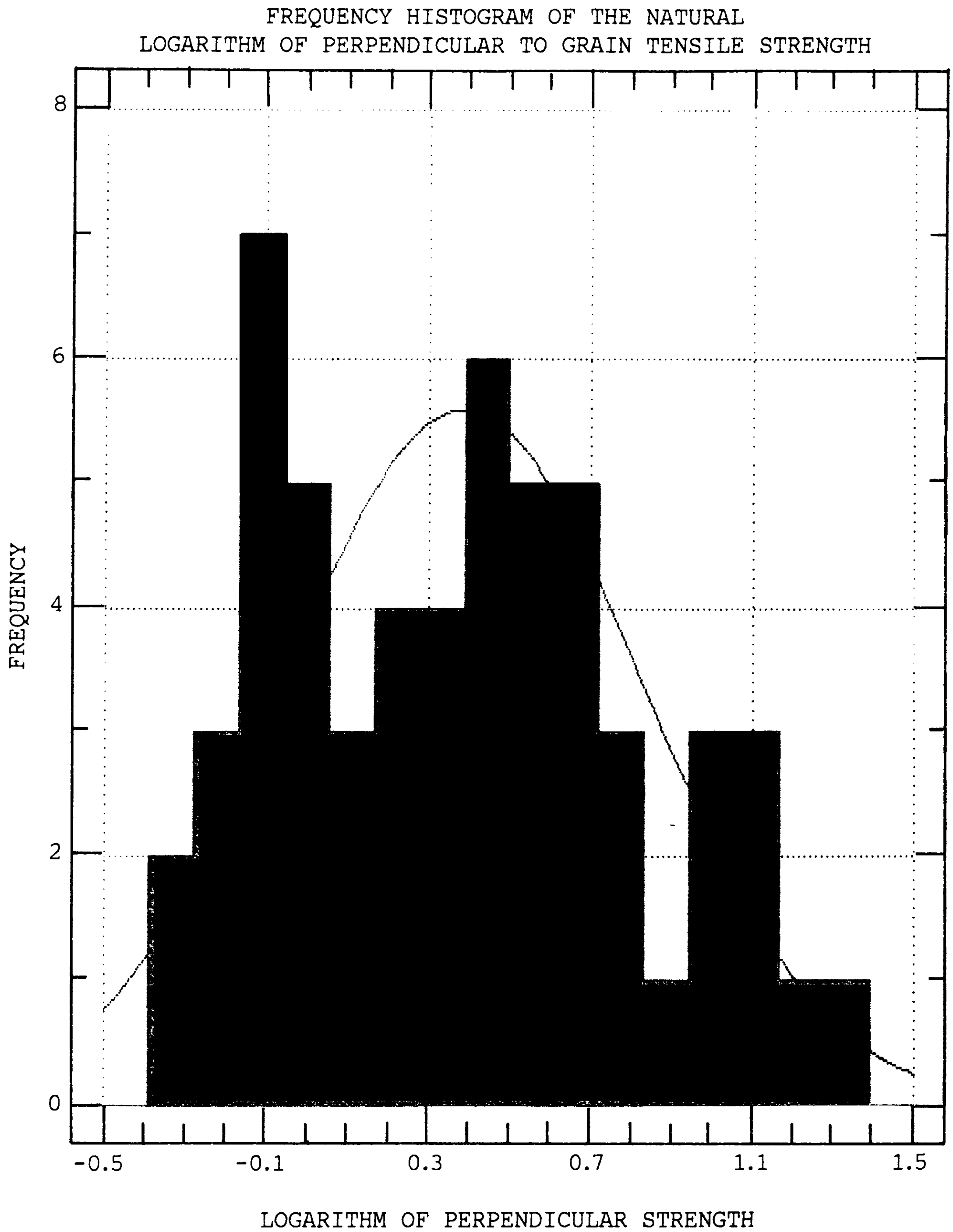


FIGURE 3.5 FREQUENCY DISTRIBUTION OF THE NATURAL LOGARITHM OF THE PERPENDICULAR TO GRAIN STRENGTH OF EUCALYPTUS GRANDIS. NORMAL DISTRIBUTION CURVE HAS BEEN FITTED.

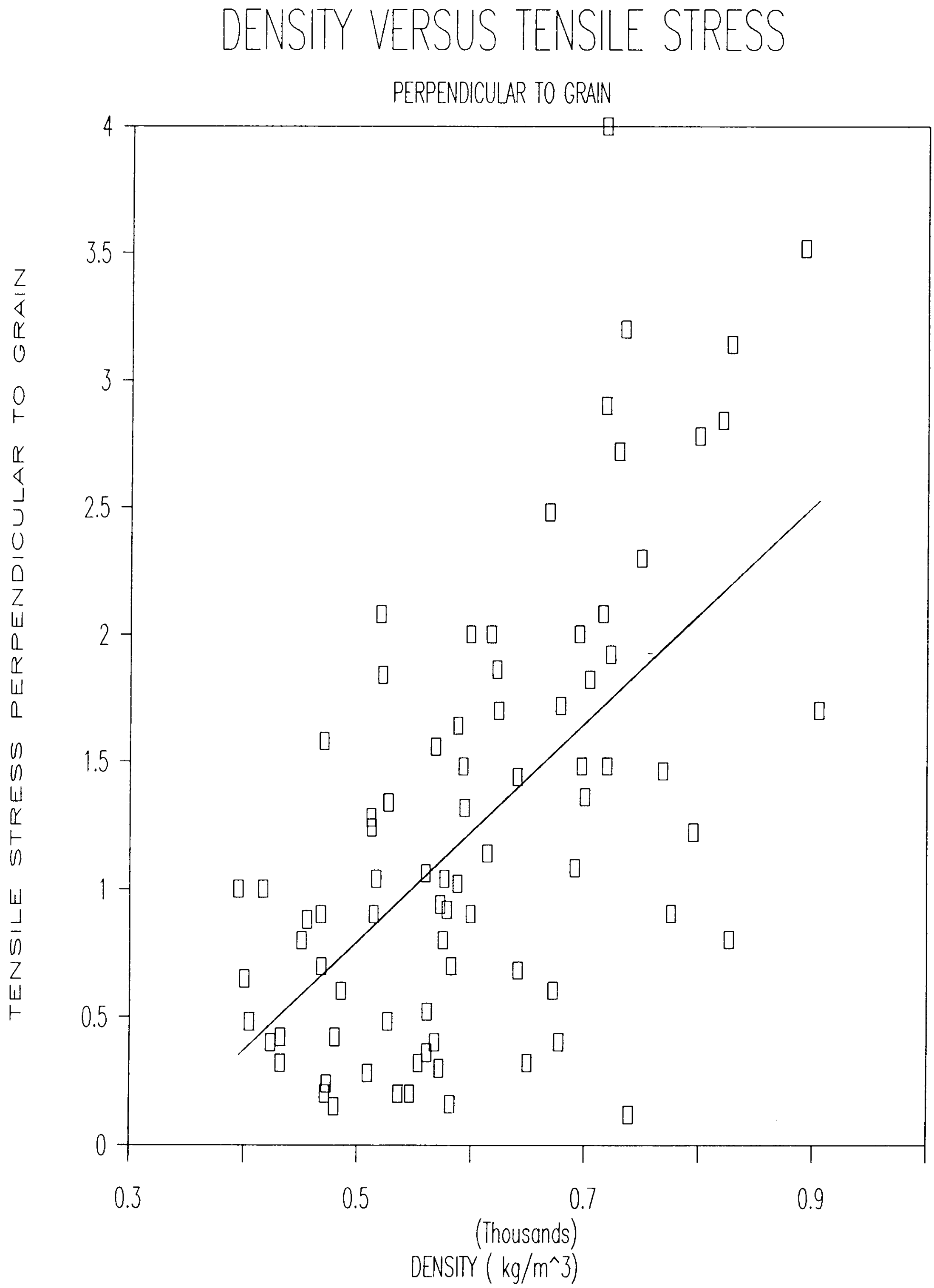


FIGURE 3.6 SIMPLE REGRESSION OF PERPENDICULAR TO GRAIN TENSILE STRENGTH VERSUS DENSITY.

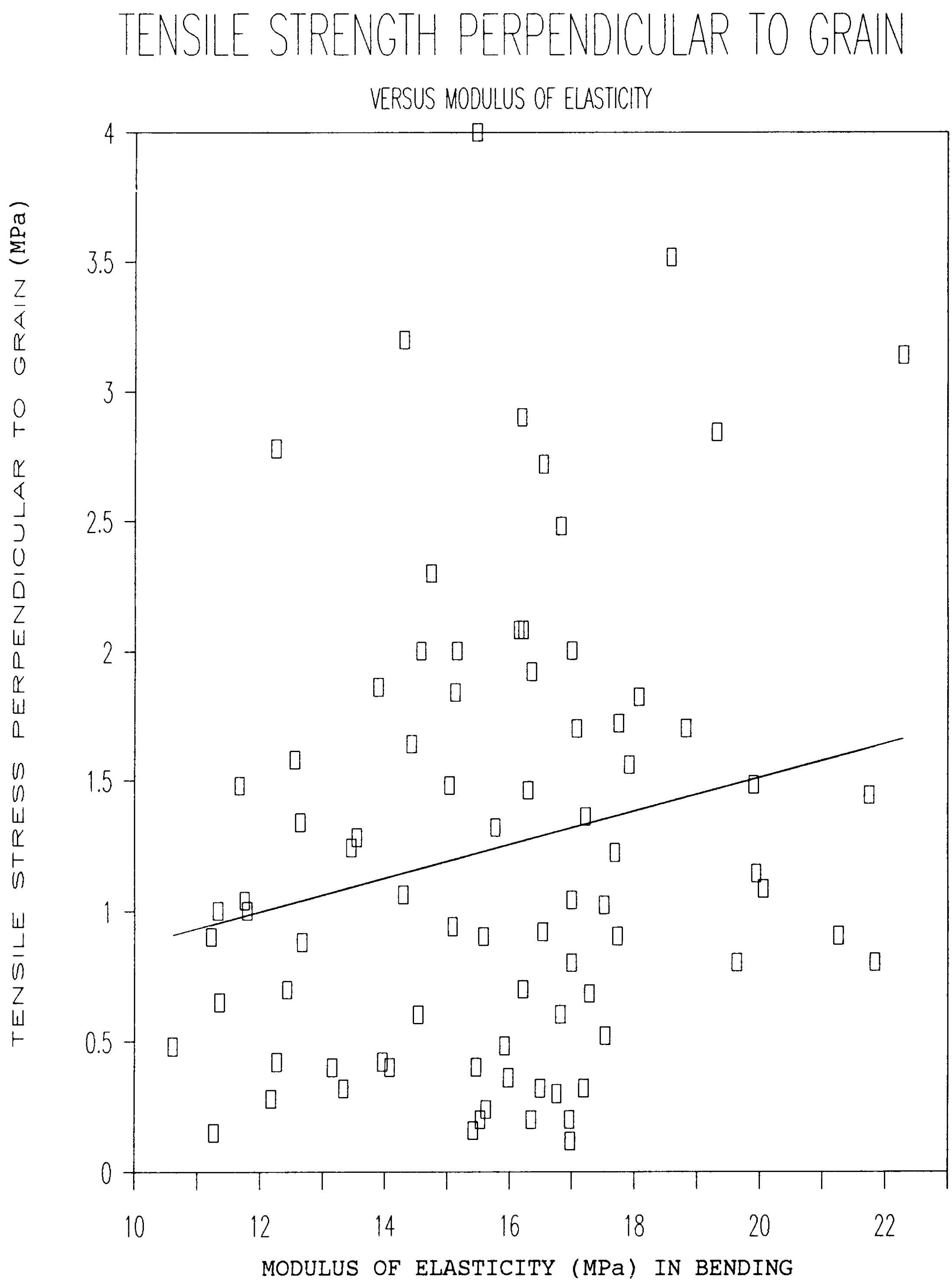


FIGURE 3.7 SIMPLE REGRESSION OF PERPENDICULAR TO GRAIN TENSILE STRENGTH VERSUS FLEXURAL MODULUS OF ELASTICITY.

4. SHEAR STRENGTH PARALLEL TO THE GRAIN.

4.1 INTRODUCTION.

Most laminated South African *E. grandis* beams fail at finger joints in the tension laminates. Delamination of the failed laminates appears to take place with the result that the beams as a whole fail. Delamination or crack propagation will take place if the shear strength or strength perpendicular to the grain is too low to transfer the forces between the failed laminate and its neighbour.

No recent information about the shear strength of *E. grandis* was available thus making it impossible to ascertain whether delamination was taking place due to this strength property being inadequate. The indications were that the strength would be low and that this low shear strength combined with a low perpendicular to the grain strength would be the major cause of delamination.

4.2 LITERATURE SURVEY.

The determination of shear strength of solid wood has been hampered by the difficulty in preparing specimens and loading methods that produce a uniform shear stress in the specimen. Many methods have been tried, but the complex stress condition at failure remains unresolved.

The specimen for the ASTM D-143[4.1] shear test (See figure 4.1)is a nearly cubical block that is stepped on one end. The unstepped portion rests on a fixed support while the stepped portion is sheared off by a plunger, which also has the function of preventing tilting of the specimen. The plunger induces stresses perpendicular to the shear plain which may strongly influence the condition of failure. Coker and Coleman[4.3] made a photoelastic analysis of the stepped block and found a very unsymmetrical stress distribution over the section where pure shear was supposed to exist. Arcan[4.2] reports that many other methods used throughout the world were considered by Rhude but none were considered to be superior to the standard ASTM test.

Arcan *et al*[4.2] developed a new method for testing material properties under uniform plane stress conditions by means of a specially shaped specimen (See Figure 4.2). The method can be used to test for pure shear. Photoelastic and strain gauge techniques were used to verify the case of pure shear for both isotropic and orthotropic specimens. A homogeneous state of pure shear was found at the critical section.

The Arcan *et al* method was used by Liu[4.4] to determine the shear strength of Sitka spruce and Douglas-fir. The relative dimensions of the test fixture and specimen were according to the recommendations of Arcan *et al*[4.2]. The total cross sectional shear area was 25 mm x 12,5 mm with the grain parallel to the direction of the applied force. Thirty specimens of each timber species were prepared. Of these 25 of each species failed at the critical section while the others failed at some material abnormality away from the critical section.

4.3 EXPERIMENTAL CONSIDERATIONS.

The ASTM[4.1] method was not practical for the timber sizes available as the boards had been planed to a thickness of 25 mm. Difficulty was found in the manufacture of specimens having the ratio given by ASTM. It was also felt that test specimens with the same ratio as the ASTM method would be too small and give very localized shear strengths, whereas the average strengths were sought. When the shear area was increased the specimens tended to tilt and it was feared that the shear area would be subjected to forces that were perpendicular to the grain.

The method described by Arcan *et al*[4.2] was rejected for practical reasons. A fairly large number of specimens was to be tested and the Arcan method requires the test specimen to be glued with epoxy into a test fixture. It was also feared that the small specimen size would be subject to damage during the manufacture as was the case with the specimens for tensile strength perpendicular to the grain.

4.4 EXPERIMENTAL PROCEDURE.

In order to obtain statistically significant values, a random sample of 100 E grandis boards, measuring 170x30 mm with lengths of about to 1,02 m, was selected from a large population from the Politsi area of the Eastern Transvaal. These specimens were planed to a standard thickness of 25 mm.

The dimensions and mass of each specimen were noted. Central point loading over a span of 600 mm was applied to the boards on flat, to obtain the modulus of elasticity for bending. To allow for distortion of the boards and/or overhang, a preload of 200 N was applied. The loading was increased by a calibrated 1,5 kN load and the increase in deflection was measured with a dial gauge. Shear deflection was ignored in the calculation of the modulus of elasticity as it is small when compared to bending deflection for the span to depth ratio under consideration.

The specimens had been conditioned for more than 3 months to an equilibrium moisture content of approximately 8-10%. The moisture content of a random sampling was determined with an electronic moisture meter and found to be in the region of 10%.

Two 320 mm lengths were cut from each board and these were narrowed down to 80 mm widths so as to fit into the grips of the Losenhauser tensile testing rig. The specimens were notched by means of a cross cut saw so that the shear area would be 80x25 mm as in Figure 4.3. Ends of the specimen were held in upper and lower grips of the testing rig. Eccentricity of the loading was avoided, as far as was humanly possible, by placing the test specimen as vertically as possible in the grips. Force was applied to the specimen at a constant rate of strain with the loading rate being kept as close to 0,20 mm/minute as possible.

4.5 EXPERIMENTAL RESULTS.

All but seven of the test specimens failed along the expected shear face. Specimens that failed elsewhere were discarded from the results.

Figure 4.4 shows the distribution of the natural logarithm of the shear strengths with a normal distribution curve superimposed. The mean strength for the distribution is 3,41 MPa and the standard deviation is 1,43 MPa. The method described by Simon[4.5] for the derivation of permissible stresses, states that the permissible stress is the fifth percentile stress divided by a factor of safety of 2,22. This method would lead to a permissible stress of 0,47 MPa which is lower than the permissible shear stress given by SABS 0163[4.6] at 1,2 MPa.

Figure 4.5 shows the plot of shear strength versus density with a linear regression line fitted. The correlation coefficient for this linear regression is 0,54 and the equation for the line is given by:

Shear strength = -0,515 + 0,0066 * (Density)

where: Shear strength is in MPa
Density is in kg/m^3

Although the correlation coefficient is fairly low, density could be used as a shear strength predictor.

Figure 4.6 shows the plot of shear strength versus flexural modulus of elasticity for bending on flat with a linear regression line fitted. The correlation coefficient for this linear regression is 0,366. As the correlation coefficient between shear strength and flexural modulus of elasticity is so low, modulus of elasticity is not recommended as a shear strength predictor.

4.6 DISCUSSION.

Although some doubt exists as to whether the specimens used for the experiments were subject to pure shear, clamping of the ends of the specimen, as was done, would have minimized the moment that the clamps could have transferred to the shear face. It is hoped that the method used here would have produced more accurate results than a modified ASTM method.

Tests done at the Council for Scientific and Industrial Research in Pretoria, and published in amendment to SABS 0163[4.6], on *E grandis* based chipboard and other panel products show that the permissible interlaminar shear for these products is in the region of 0,4 MPa.

The permissible shear stress obtained in the experiments described here is very similar to the values obtained for *E grandis* based panel products where values of 0,40 MPa are recommended. The author is of the opinion that panel products and especially the fibre boards should have an interlaminar shear strength that is at least as high as the horizontal shear strength of the sawn timber, as all the natural strength reducing features have been removed and replaced by a more homogeneous defect, namely the glue surface. With this in mind the author recommends that a further series of tests be undertaken to determine permissible shear stresses and that the ASTM method be used.

Failure of a finger joint in a laminate of a laminated beam will cause the forces in that laminate to be transferred to adjacent laminates through horizontal shear and stress perpendicular to the grain. The low shear strength of the *E. grandis* tested here, shows that in most cases the horizontal shear strength will be too low to transfer the forces and delamination of the failed laminate will take place.

A failed finger joint in a laminate of a beam is equivalent to a butt joint in that laminate. Leicester[4.7] has shown that the ultimate stress that will cause crack propagation in or between the laminates of a beam with an edge butt joint can be given by:

$$f_{t(ult)} = \frac{0,15 \text{ x density}}{(\pi \text{ x } 2a)^{0,5}}$$

and that of an inner laminate with a butt joint by:

$$f_{t(ult)} = \frac{0,15 \times density}{(\pi \times a)^{0,5}}$$

Where: $f_{t(ult)}$ is in MPa
density in kg/m^3
a is the thickness of the laminate in mm

If these formulas are applied to the *E. grandis* used in this study and a high value of 800 kg/m^3 for the density is used, the ultimate strength of a laminate with an edge butt joint would be 10,2 MPa and that of an inner laminate with a butt joint, 14,4 MPa. Even if one assumes that these strengths are the mean strengths of butt joints, they are very low and indicate that in most cases fracture of the failed laminate will occur. This confirms the observation, that failure of a finger joint in a laminate causes delamination of that laminate, and that this is due to the low shear strength and low tensile strength perpendicular to the grain.

4.7 ADDITIONAL EXPERIMENTAL WORK.

The large discrepancy between the permissible stresses found in the original test programme and the permissible stresses given in the South African timber design code SABS 0163[4.6] was of concern and it was felt that further tests should be undertaken to validate the code values.

As bolted connections had been tested as part of another project, the results of these tests were examined to see whether they could not be used to obtain the magnitude of the permissible shear stress. Twelve millimeter black bolts were placed at a distance of 84 mm from the end of the test specimen as in Figure 4.7. Although the distance to the end of the bolted member was seven times the diameter all the connections eventually failed in shear as shown in Figure 4.7. It can be expected that the shear strength obtained in this way would be higher than with the ASTM[4.1] method, as a certain amount of wedging of the bolt head and washer will occur.

The shear strengths were assumed to have a log-normal distribution and the distribution of the natural logarithm of the shear strength is shown in Figure 4.8. Using the method described by Simon[4.5] a permissible shear stress of 0,78 MPa results. This is less than the permissible shear stress of 1,2 MPa given in the design code SABS 0163[4.6].

4.8 CONCLUSION.

Although the failure shear strength of the bolted connections is not conclusive proof that the permissible shear stress, given in the code

SABS 0163, is incorrect, this, together with the value obtained from the shear strength experiments, does cast some doubt on the value and is of concern.

This study, however, is about the behaviour of a laminate in a beam and is also concerned about the distribution of the shear strength. The shear test values and bolt strength values have shown that the shear strength is very low and will, in most cases, lead to delamination of the outer laminate if failure is initiated in the outer laminate. For inner laminates the shear strength is less critical but will still have to be assigned a strength that is less than the value given in the code.

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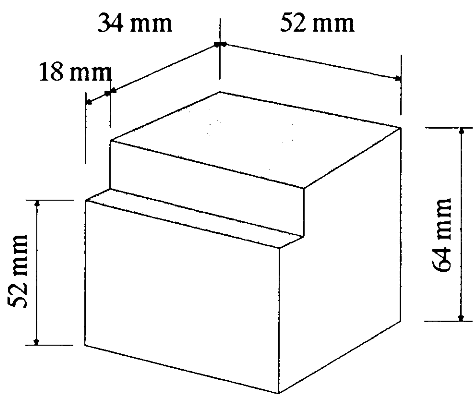
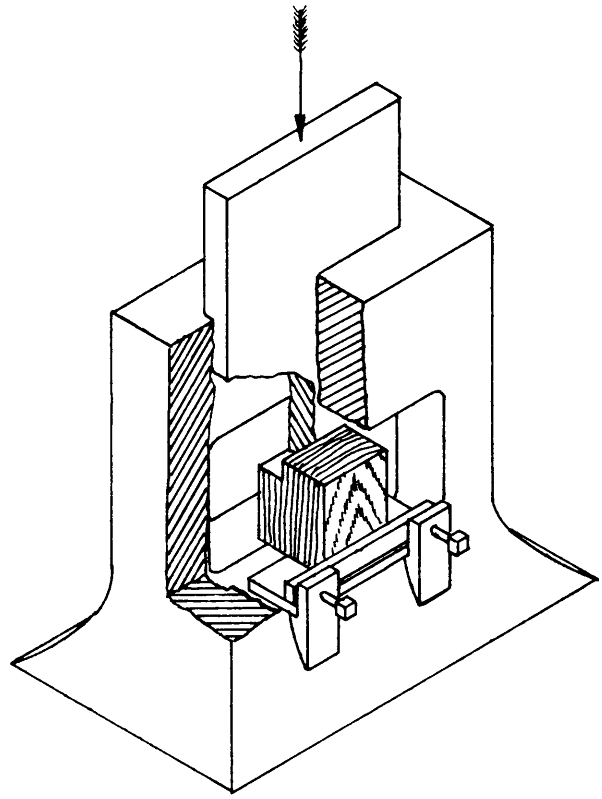


DIMENSIONS OF STANDARD ASTM SHEAR BLOCK.



METHOD USED TO TEST SHEAR STRENGTH.

FIGURE 4.1: STANDARD ASTM SHEAR BLOCK

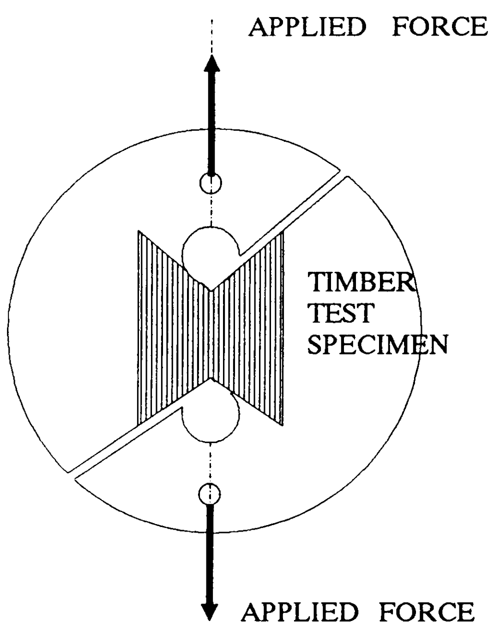


FIGURE 4.2: ARCAN SHEAR TEST METHOD

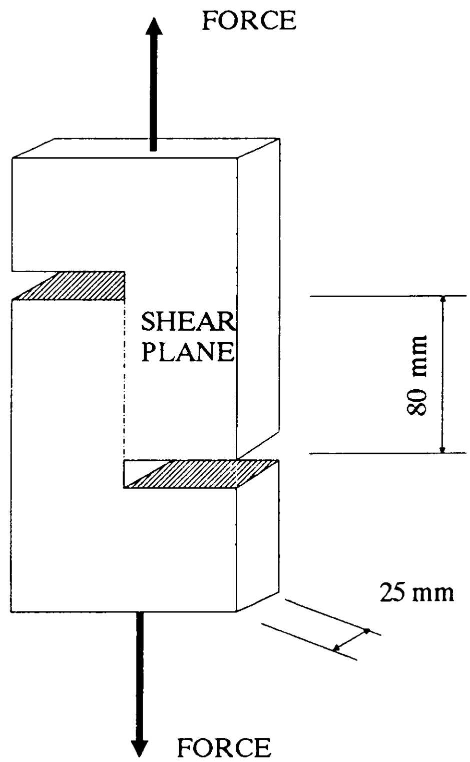


FIGURE 4.3: SHEAR SPECIMEN USED.

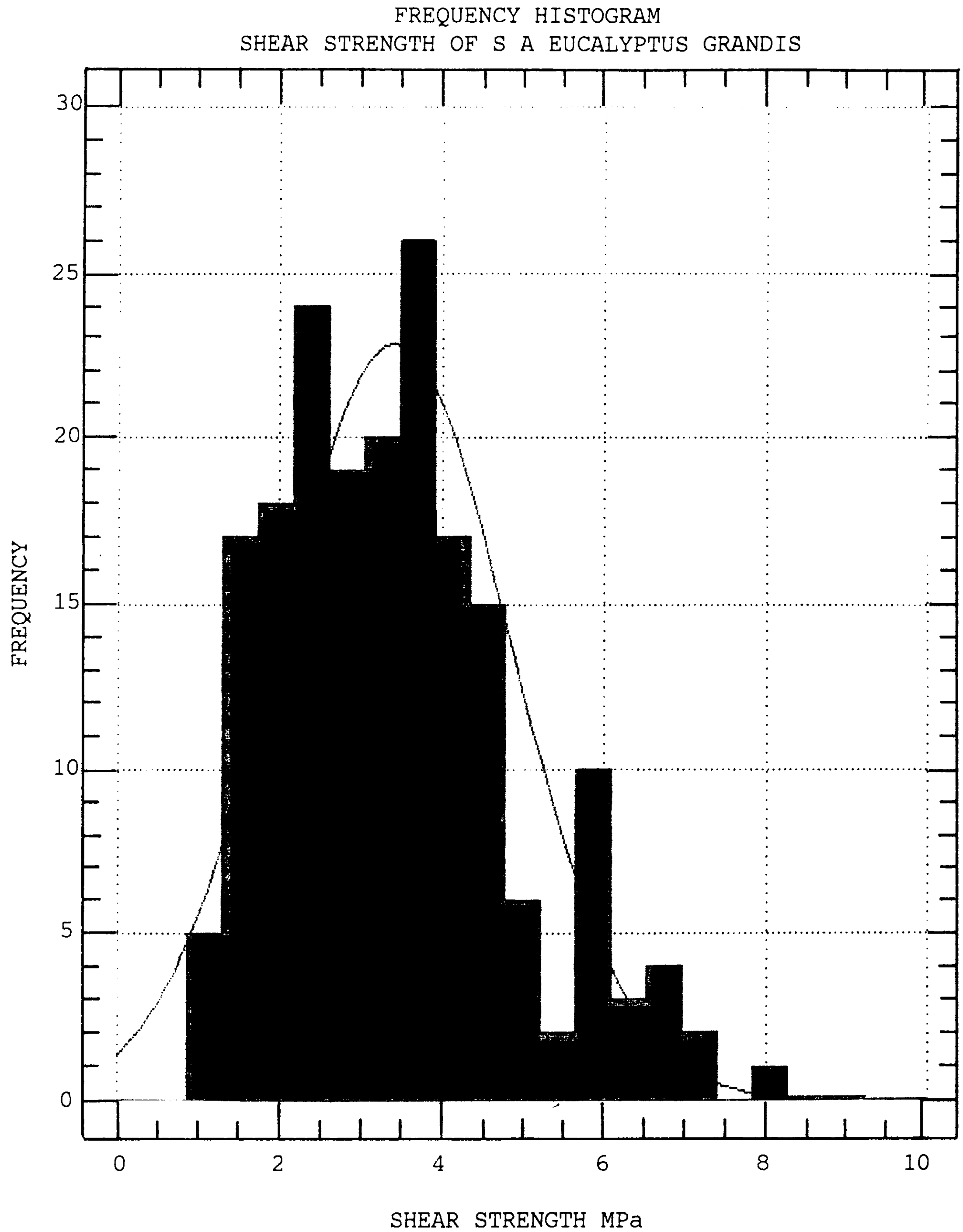


FIGURE 4.4 DISTRIBUTION OF SHEAR STRENGTH OF TEST SPECIMENS. NORMAL DISTRIBUTION CURVE HAS BEEN FITTED.

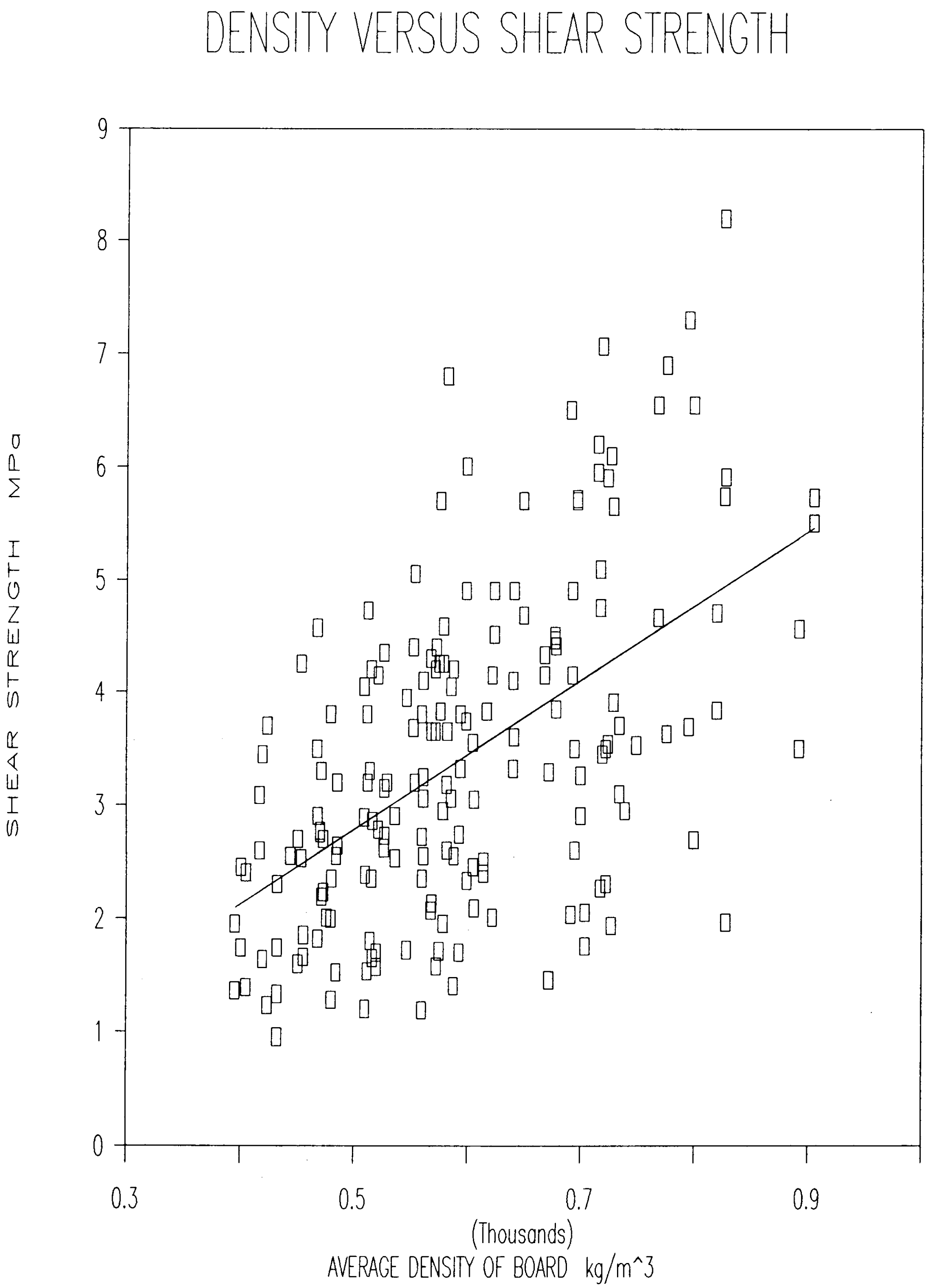


FIGURE 4.5 REGRESSION OF SHEAR STRENGTH VERSUS DENSITY FOR TEST SPECIMENS.

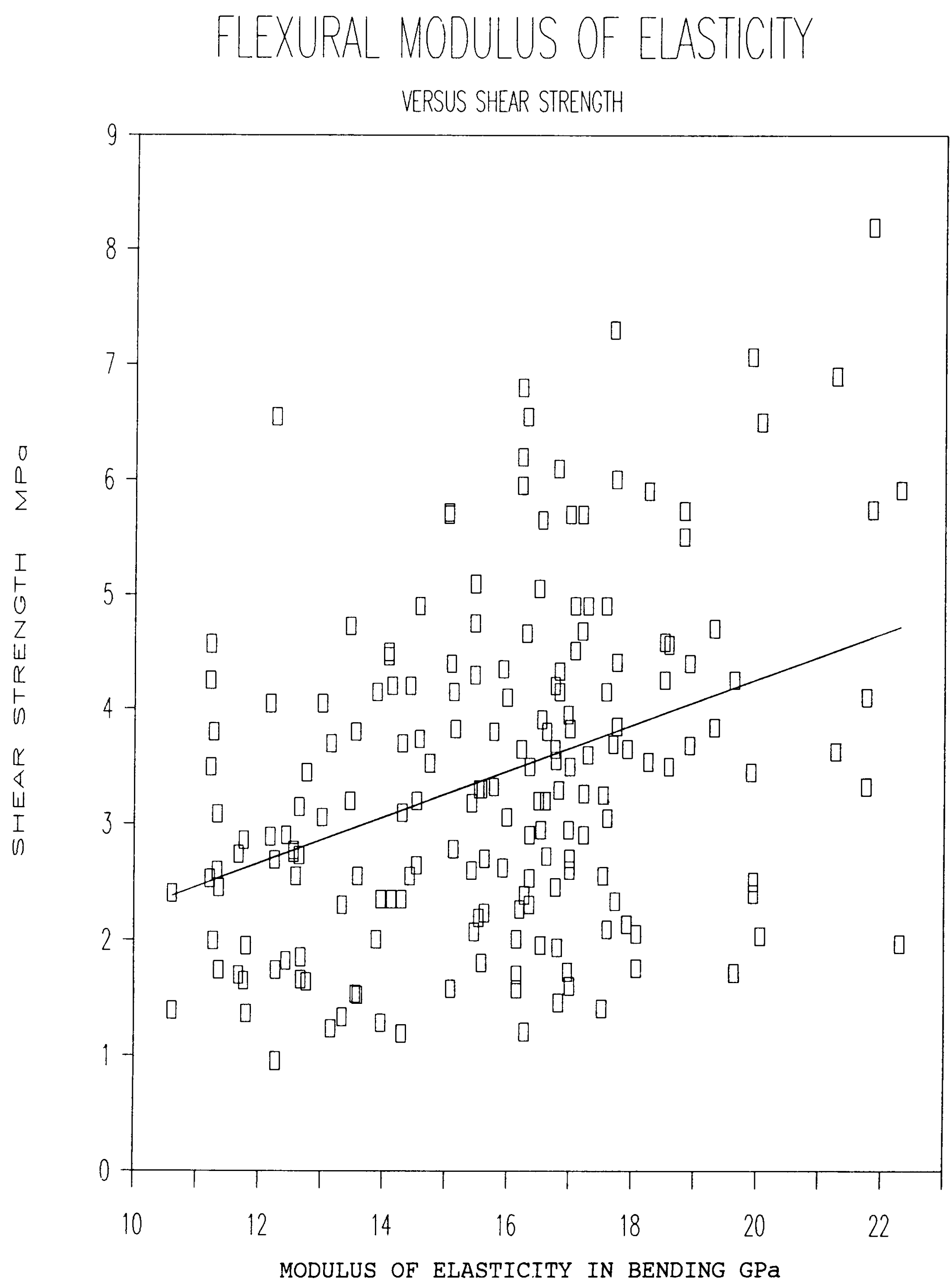


FIGURE 4.6 SIMPLE REGRESSION OF SHEAR STRENGTH VERSUS FLEXURAL MODULUS OF ELASTICITY FOR TEST SPECIMENS.

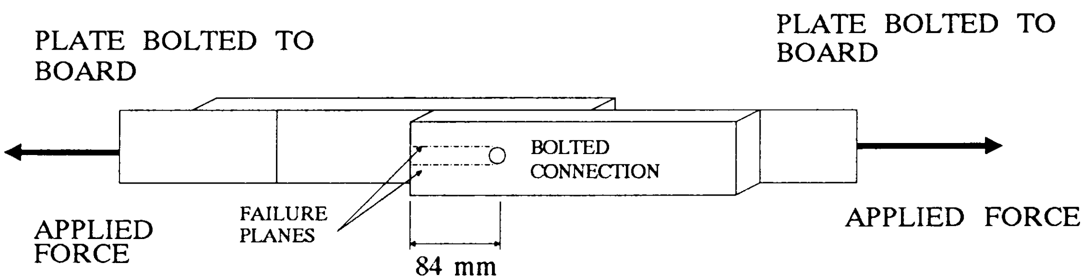


FIGURE 4.7: BOLT TEST SPECIMEN.

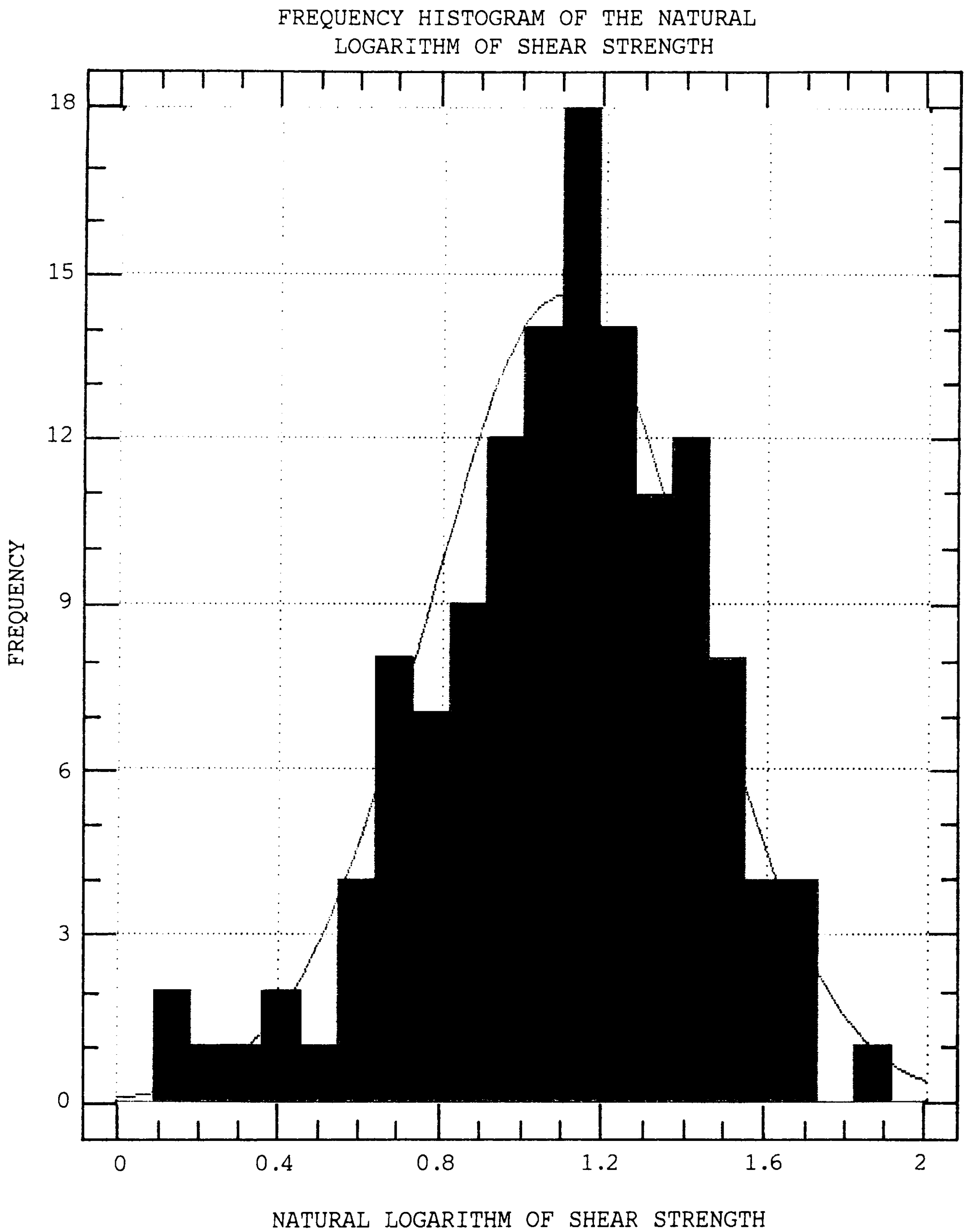


FIGURE 4.8 DISTRIBUTION OF THE NATURAL LOGARITHM OF SHEAR STRENGTH OF THE TIMBER IN A BOLTED CONNECTION.

5. STRENGTH OF FINGER JOINTS

5.1 INTRODUCTION

Strength reducing features in timber, such as knots, slope of grain etc. have always been of concern to the structural engineer. When designing a timber structure these features can be critical in members that are subjected to tensile forces. In an effort to minimise the effect of such a feature and/or to increase the length of available timber, it is necessary to end-joint timber boards. Scarf joints were used, but were found to be too expensive as they wasted material. Finger joints have provided the engineer with an efficient joint that works well in timber that has a fairly low clear specimen strength. Clear specimen strength is that strength which the timber will attain when all visible strength reducing features have been removed.

Phenol resorcinol formaldehyde (p.r.f) is the adhesive most commonly used in the manufacture of finger joints in South Africa. The glue-line strength obtained when this adhesive is used in higher strength grade or higher density timber has proved to be too low to realise the full potential strength of the timber. Van Rensburg *et al*[5.2] have shown that the mean tensile strength of a *E. grandis* finger joints manufactured with p.r.f remains fairly constant irrespective of the density of the timber (See Figure 5.1). The correlation coefficient between density and tensile strength of finger joints manufactured with p.r.f is very low and a value of 0,179 was obtained by van Rensburg et al.

Fears were expressed that the small specimen p.r.f glued finger joints would give misleading strength values that were greater than those that could be expected from full sized specimens. The specimens used by van Rensburg et al had a neck area of 22,5 x 50 mm whereas full sized boards would have finger joints with widths of up to 165 mm.

5.2 MOTIVATION FOR FURTHER TESTS

The weak correlation between tensile strength of finger joints in *E. grandis* and density made density a very bad predictor of finger joint strengths. The stronger correlation between tensile strength of *E. grandis* (See Figure 2.3) and the flexural modulus of elasticity, gave rise to the question whether the flexural modulus of elasticity could be used as a tensile strength predictor for full sized finger joints.

The profiled small specimens tested by van Rensburg *et al* gave strengths that were in excess of strengths obtained from tests on full sized timber beams by Grunow[5.1]. It was suspected that a size effect was present that would have to be taken into account when predicting the strength of full width beams. Any size effect would become apparent when full width finger joints were tested.

The possibility that a finger joint had a local stiffening effect was also considered as this would, when the finger joint is part of a beam, cause the finger joint to be subjected to higher stresses than anticipated. This would cause the beam to fail at a lower stress than the strength of the finger joint would suggest. No local stiffening effect, however, was expected as the glue line is very thin.

5.3 EXPERIMENTAL WORK

The aims of the experimental work could be divided into three separate categories.

i) To find a method of predicting the strength of finger joints in E grandis that have been glued with p.r.f..

ii) To discover whether the tensile strength of a finger joint in *E. grandis* is governed by a size effect.

iii) To ascertain whether a finger joint has any localised stiffening effect on the *E. grandis* board.

The test results as given in Section 2 have shown that the flexural modulus of elasticity could be used as a predictor of tensile strength of full sized specimens with defects. The possibility, that either the lower or the higher modulus of elasticity of the two boards that are joined by a finger joint, would govern the strength of the finger joint, was considered. To this end the flexural modulus of elasticity for bending on flat as well as the density of both boards was determined.

Two standard board widths were chosen to ascertain whether any width effect, that would influence the strength of a finger joint, could be found. One hundred specimens of each of, a 64 mm wide and of a 88 mm wide finger jointed board, were tested for tensile strength. Boards were planed to a standard thickness of 22 mm.

To ascertain any localised stiffening effect of a finger joint one specimen of each board size was chosen, strain gauges pasted on both faces of the finger joint and the boards on either side of the finger joint and the relative strains under tension measured. The relative strains were then compared so that a comparative stiffness could be found.

5.4 EXPERIMENTAL RESULTS

The finger jointed boards were to have been tested in the horizontal tensile testing rig, described in Section 2, that uses rubber friction pads to hold the specimen. No visible damage is done to the specimen by the rubber grips and in most cases failure of the specimen occurs at the finger joint or major defect away from the grip. The surfaces of the planed boards proved to be too smooth for enough frictional force to be applied with the result that the boards slipped before failure stresses could be reached.

Tensile tests were then carried out on an Instron vertical tensile testing rig that uses patterned metal grips to hold both ends of the specimen. These metal grips have a wedging action when longitudinal tensile forces are applied. The lateral forces so applied on either side and end of the specimen increase as the londitudinal force increases. These forces became so large that the material under the grips was crushed. Seventy five percent of the specimens failed at the grip due to the material being crushed to such an extent that loss in strength at this crushed section was greater than the loss in strength due to the finger jointing. Only about 25 of each specimen size failed at the finger joint and these were used for the further calculations. Specimens that failed due to grip crushing were discarded.

The results for each specimen size were evaluated seperately and the mean tensile strengths and standard deviations of the finger joints were compared. The mean tensile strengths for the two specimen widths differed by only 0,4 MPa. Data of the tensile strength, density and flexural modulus of elasticity for the two specimen widths were combined. The tensile strength of the combined test sample was evaluated and a normal distribution fitted. The mean strength of the finger joints for the combined data was 37,73 MPa with a standard deviation of 13,35 MPa. (See Figure 5.2) The finger joint tests done by van Rensburg *et al* resulted in a mean tensile strength for the finger joints of 36,4 MPa and a standard deviation of 9,0 MPa. (See Figure 5.3) The difference in the mean tensile strength seemed to indicate that the material used for the full sized specimens was of a slightly higher average density than that used by van Rensburg *et al* as Van Rensburg *et al* had shown that the higher density timber not only had a slightly higher strength but also a higher variation in strength. The mean density for the full sized specimens was 601 kg/m^3 whereas the mean density for the specimens used by van Rensburg *et al* was in the region of 566 kg/m^3. (van Rensburg *et al* grouped specimens.)

Figure 5.4 and Figure 5.5 show plots of tensile strength of p.r.f. glued finger joints versus lower density and higher density of the two boards respectively. Linear regression lines are fitted and the correlation coefficient between density and tensile strength of finger joints for the lower density member is 0,11 and that of the higher density member is 0,08. These results are very much in keeping with the correlation coefficient between density and tensile strength, for p.r.f glued finger joints, of 0,179 as found by van Rensburg *et al*.

Figure 5.6 and Figure 5.7 show the plots of tensile strength of p.r.f. glued finger joints versus flexural modulus of elasticity for the less stiff and for the stiffer member respectively. Linear regression lines are fitted and the correlation coefficient between flexural modulus of elasticity and tensile strength of finger joints for the less stiff member is 0,32 and for the stiffer member 0,24.

The strain gauges that were used to determine the stiffness of the finger joint relative to the stiffness of the boards on either side of the joint showed that the finger joint had no localised stiffening effect. The stiffness of the finger joint was found to be equal to the average of the the two boards.

5.5 DISCUSSION

Although the number of tests was limited, the conclusion can be drawn that no discernible width or size factor affects the strength of finger joints and that small test specimens can be used to determine the strength of finger joints. The tests done by van Rensburg *et al*[5.2] can be used as in indicator of the expected strength of finger joints that have been glued with phenol resorcinol formaldehyde. This is in keeping with the preliminary findings of Moody *et al*[5.3] who found that the laminated beams used for their study showed no discernible width effect. Unpublished results of tensile strength tests done at Oregon State University led them to believe that a width effect did exist and that the exponent *z* of the following formula was equal to nine.

$$R = R_0 K \left(\frac{d_0}{d}\right)^{1/x} \left(\frac{l_0}{l}\right)^{1/y} \left(\frac{w_0}{w}\right)^{1/z}$$

Where: R is the strength of the beam with dimensions d, l, w;
R_0 is the strength of the standard beam of dimensions d_0, l_0, w_0;
K is the factor that indicates the type of loading;
d_0, l_0, w_0 are the dimensions of the standard beam;
d, l, w are the dimensions of the beam under consideration;
x, y, z are the exponents that were to be determined.

If this formula is applied to the test results obtained by van Rensburg et al and the test results of this study and the exponent *z* is assumed to be nine, a reduction of 6 % could have been expected for the 88 mm wide specimen and 3 % for the 64 mm wide specimen. This reduction in tensile strength could not be discerned in the tests conducted in this study. The widest *E. grandis* section available in South Africa has a width of 165 mm. If the exponent z in the formula above is assumed to be equal to nine, a strength reduction of 14 % could be expected. This is a significant reduction and further experimental testing should be undertaken using the widest available *E. grandis* boards.

From Figures 5.4 to 5.7 it is clear that neither density nor flexural modulus of elasticity should not be used as a finger joint strength predictor. The best correlation between density and tensile strength was 0,11 for the lower density while the best correlation between flexural modulus of elasticity and tensile strength of finger joints was 0,32 for the less stiff member. Both these correlation coefficients are very low. As this study uses the strength of finger joints and the flexural modulus of elasticity in the simulation of beam strength it was hoped that a good correlation between strength of finger joints and flexural modulus of elasticity could be found so that these properties could be positively correlated in the simulation. The correlation between modulus of elasticity and finger joint strength was found to be so weak that for practical purposes random finger joint strengths could be assumed.

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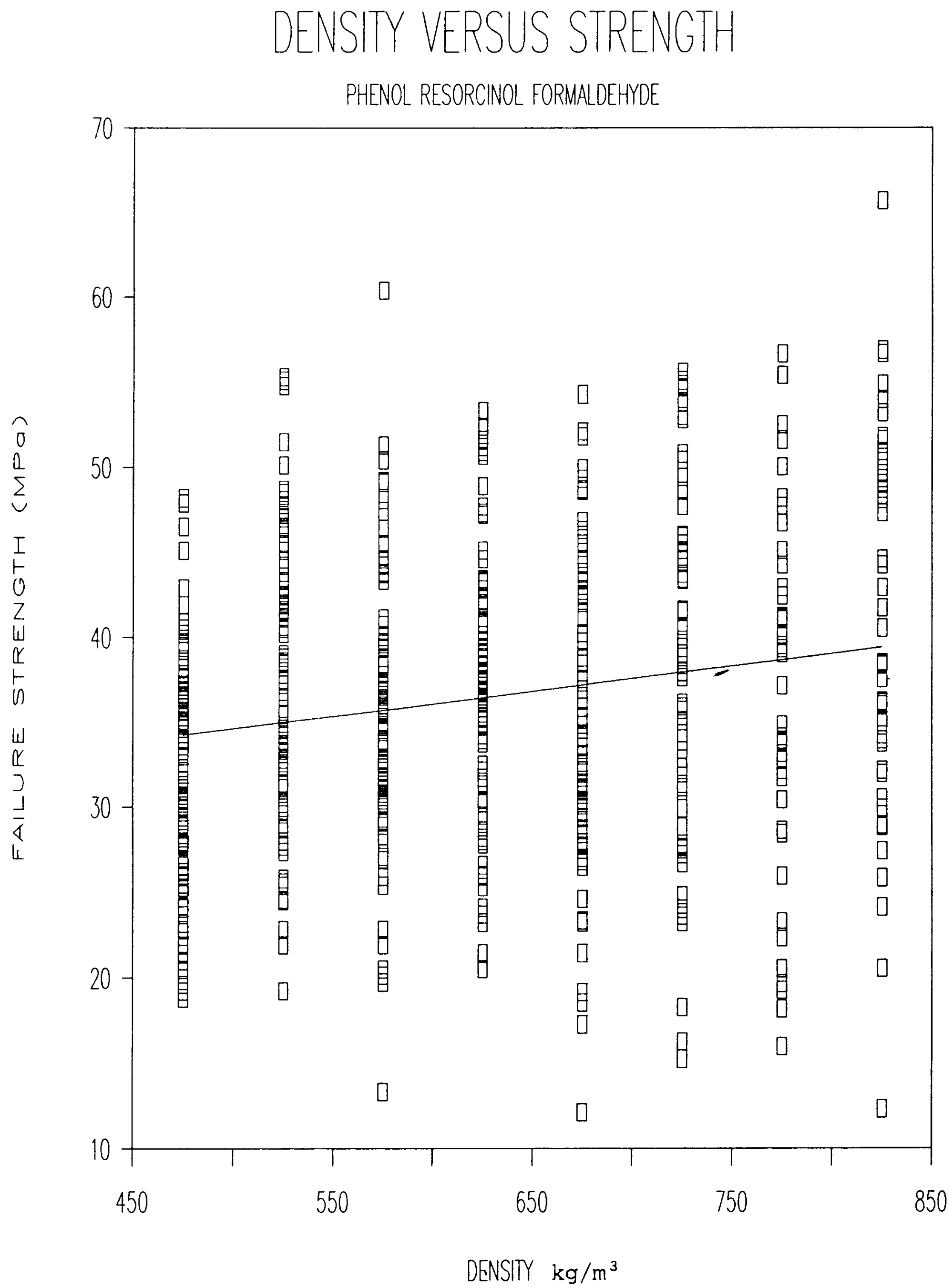

FIGURE 5.1 SIMPLE LINEAR REGRESSION OF TENSILE STRENGTH VERSUS DENSITY OF SMALL SPECIMEN FINGER JOINTED EUCALYPTUS GRANDIS.

FREQUENCY HISTOGRAM OF TENSILE STRENGTH
FULL SIZED P.R.F. GLUED FINGER JOINTS

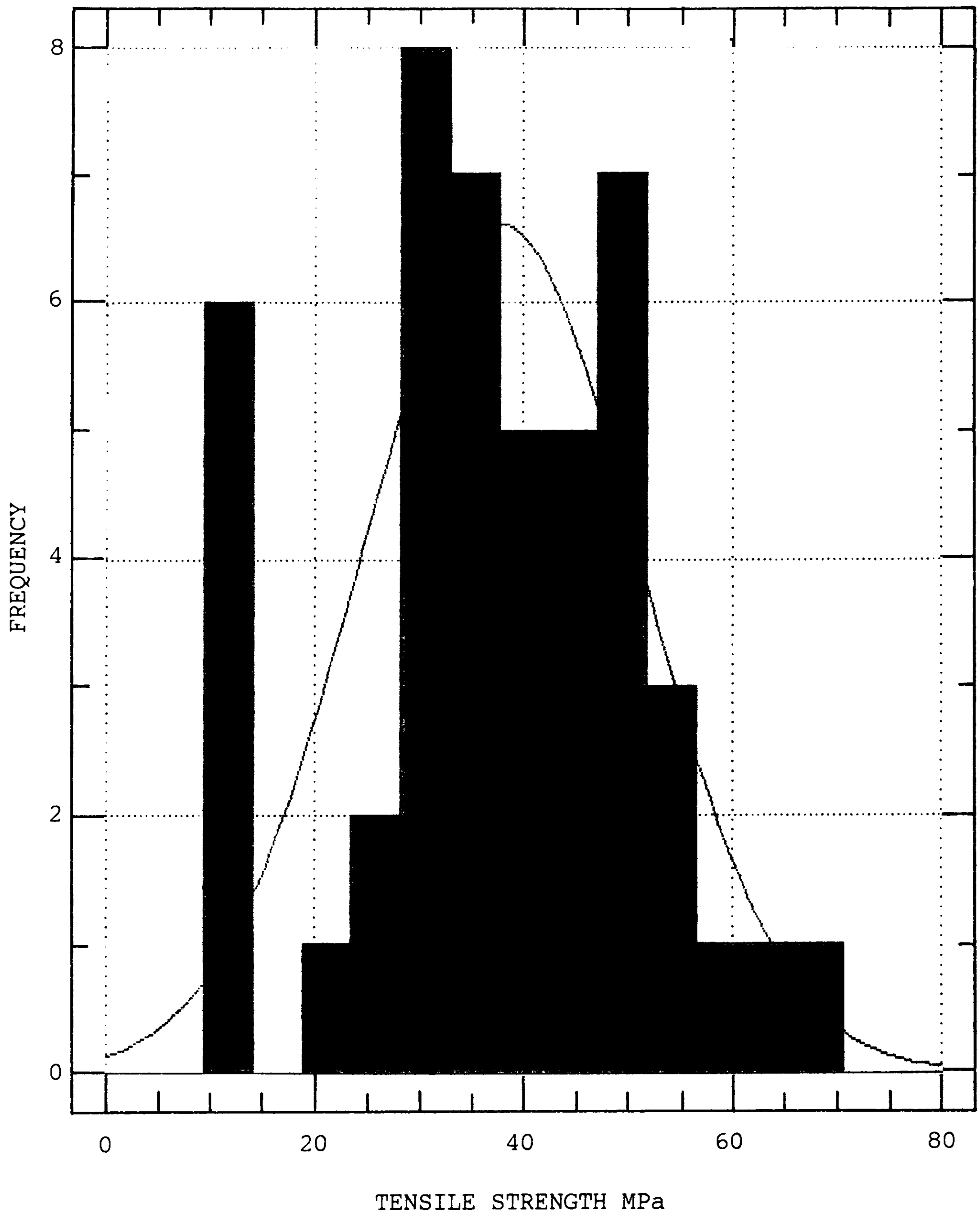

FIGURE 5.2 DISTRIBUTION OF TENSILE STRENGTH OF FULL SIZED EUCALUPTUS GRANDIS FINGER JOINTS.

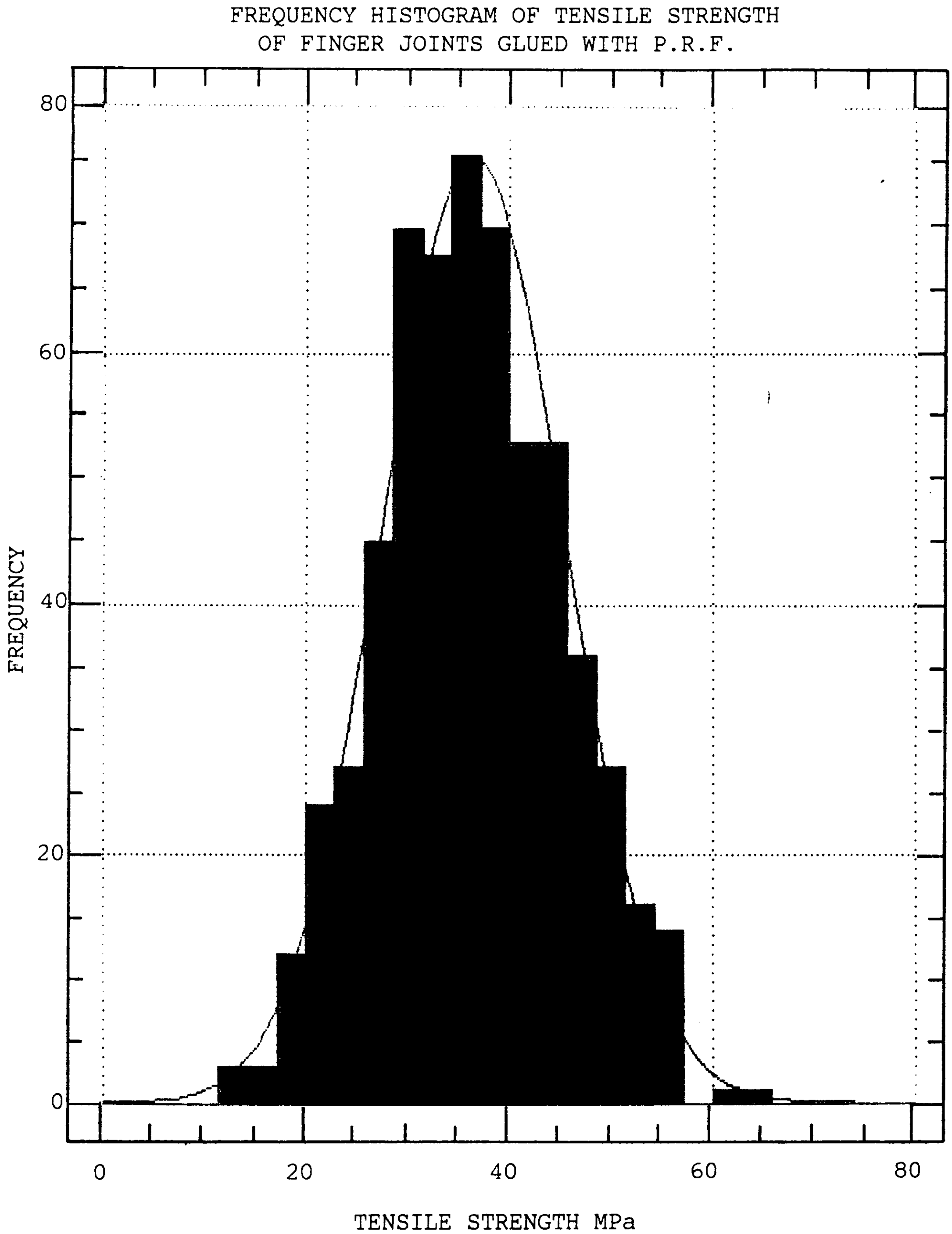

FIGURE 5.3 DISTRIBUTION OF TENSILE STRENGTH OF SMALL SPECIMEN SIZE EUCALYPTUS GRANDIS FINGER JOINTS.

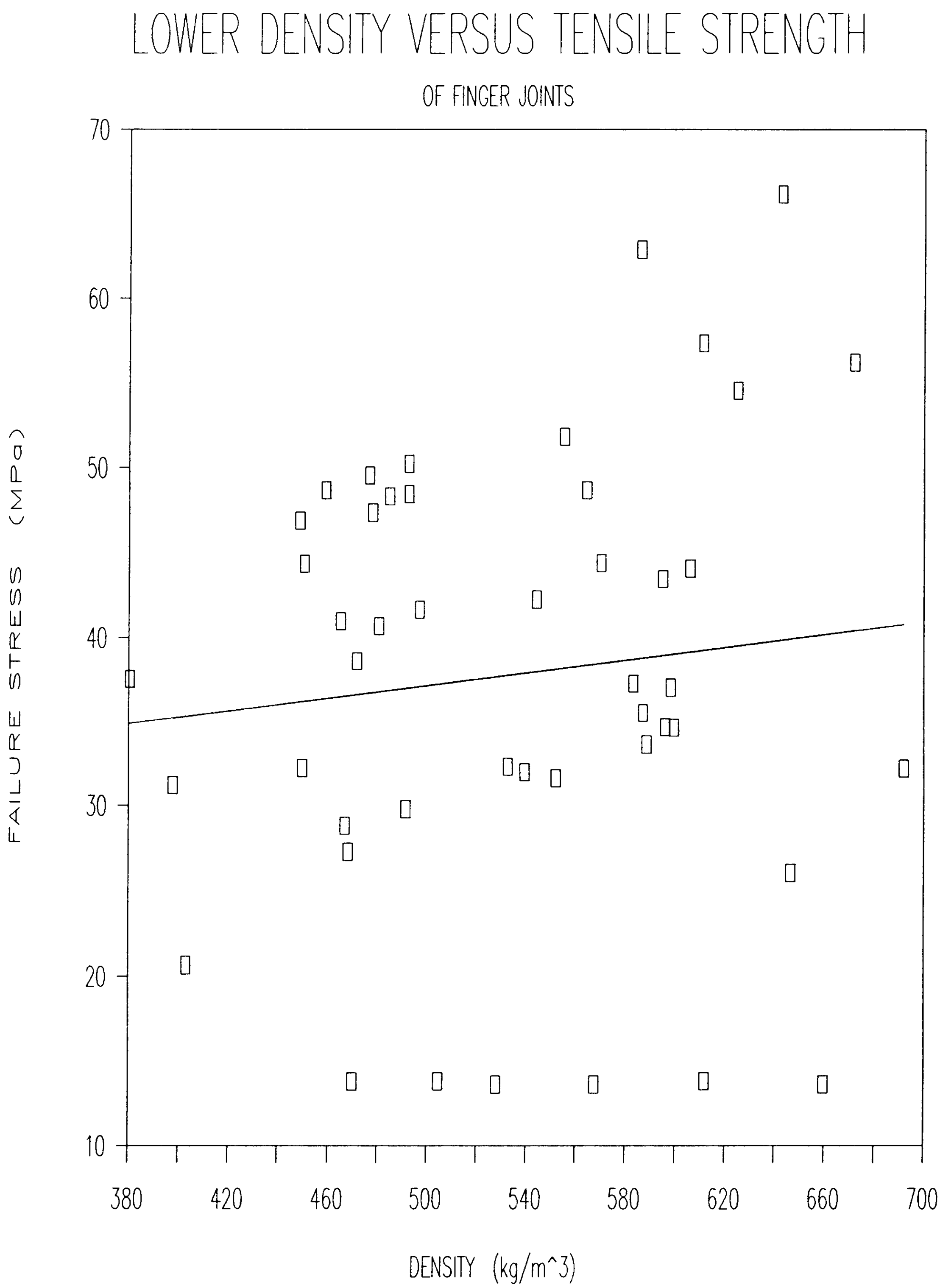

FIGURE 5.4 SIMPLE LINEAR REGRESSION OF TENSILE STRENGTH OF FULL SIZED FINGER JOINTS VERSUS DENSITY OF THE LESS DENSE BOARD.

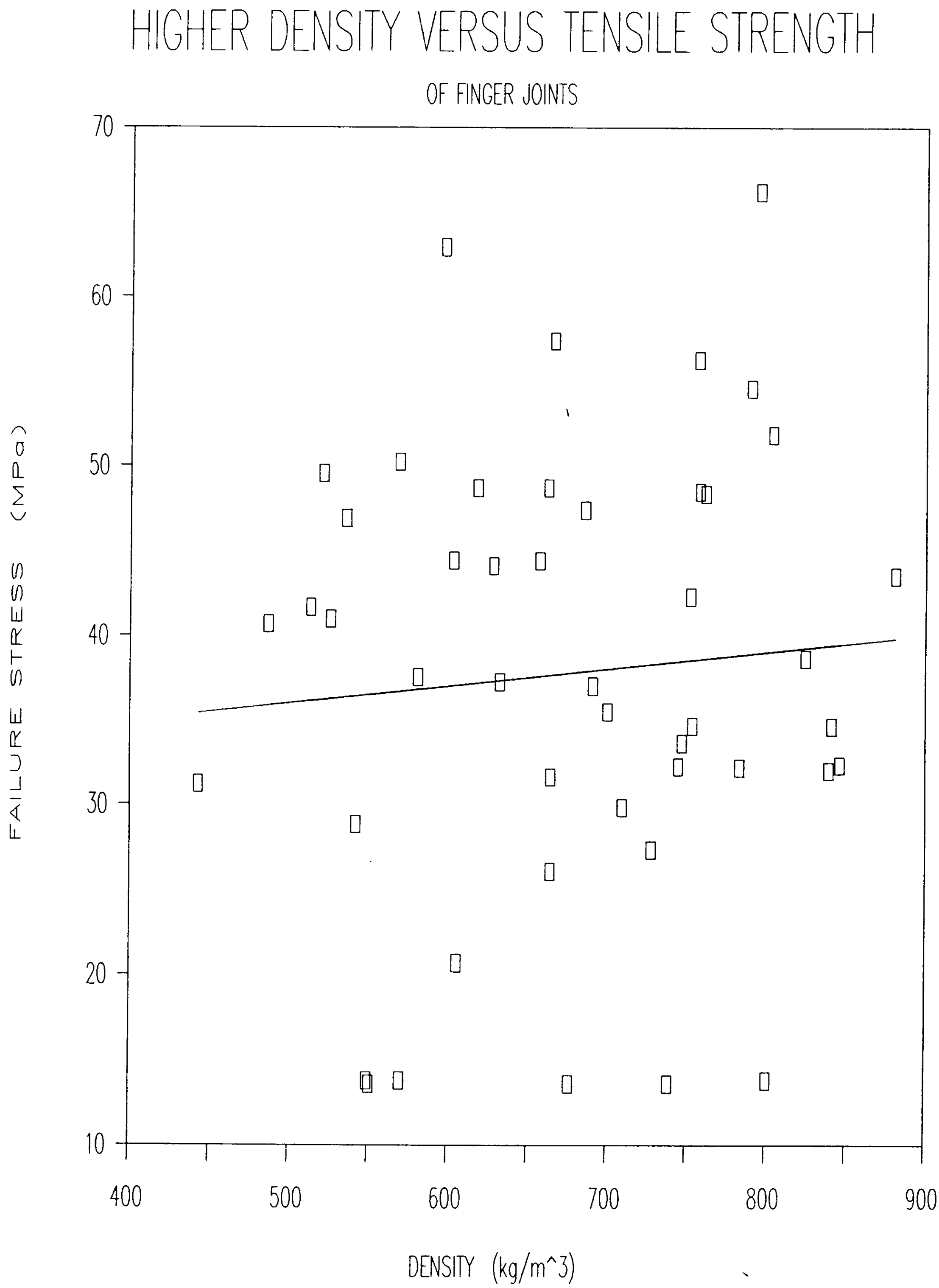

FIGURE 5.5 SIMPLE LINEAR REGRESSION OF TENSILE STRENGTH OF FULL SIZED FINGER JOINTS VERSUS DENSITY OF THE DENSER BOARD.

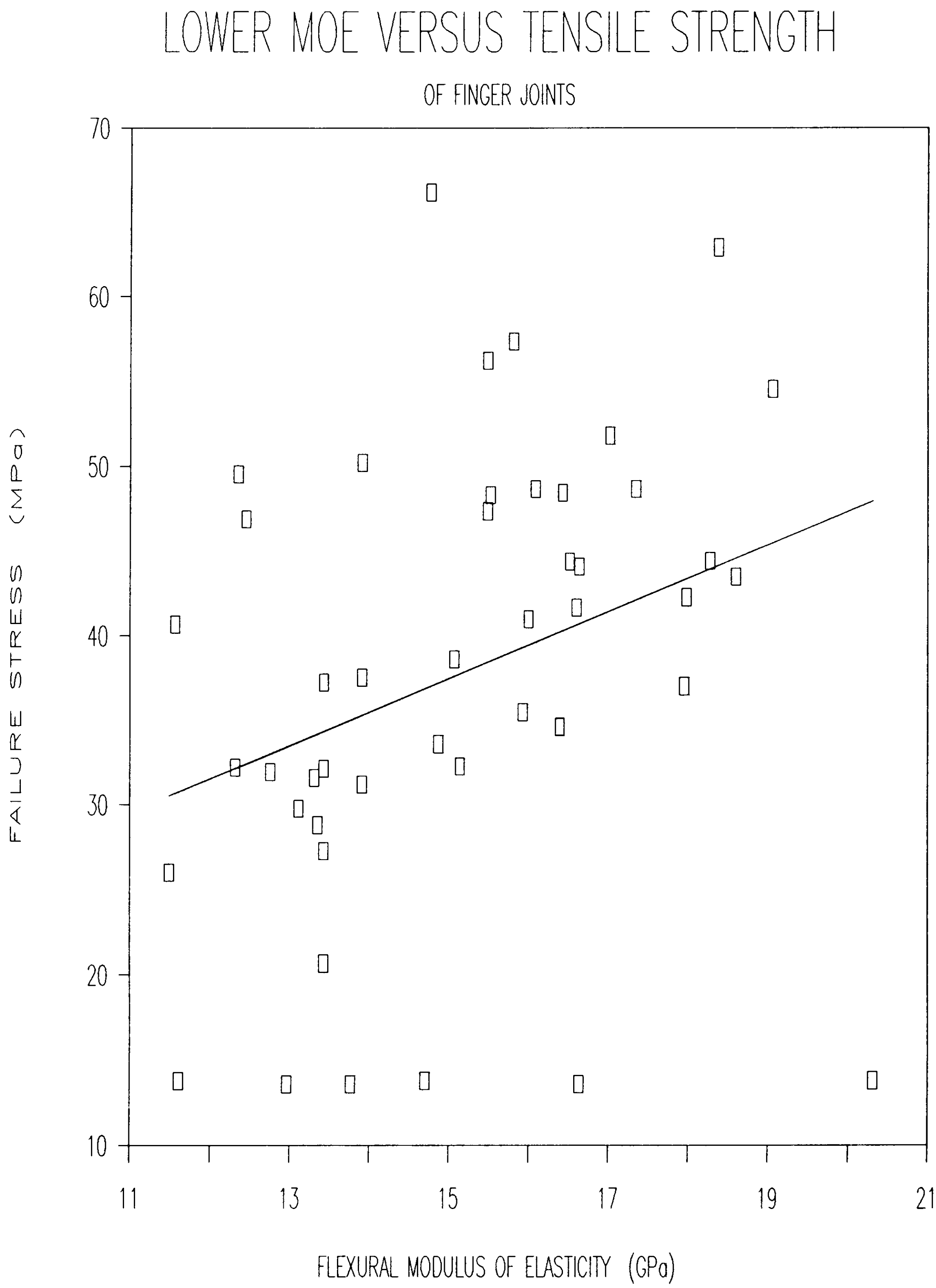

FIGURE 5.6 SIMPLE LINEAR REGRESSION OF TENSILE STRENGTH OF FULL SIZED EUCALYPTUS GRANDIS FINGER JOINTS VERSUS MODULUS OF ELASTICITY OF LESS STIFF BOARD.

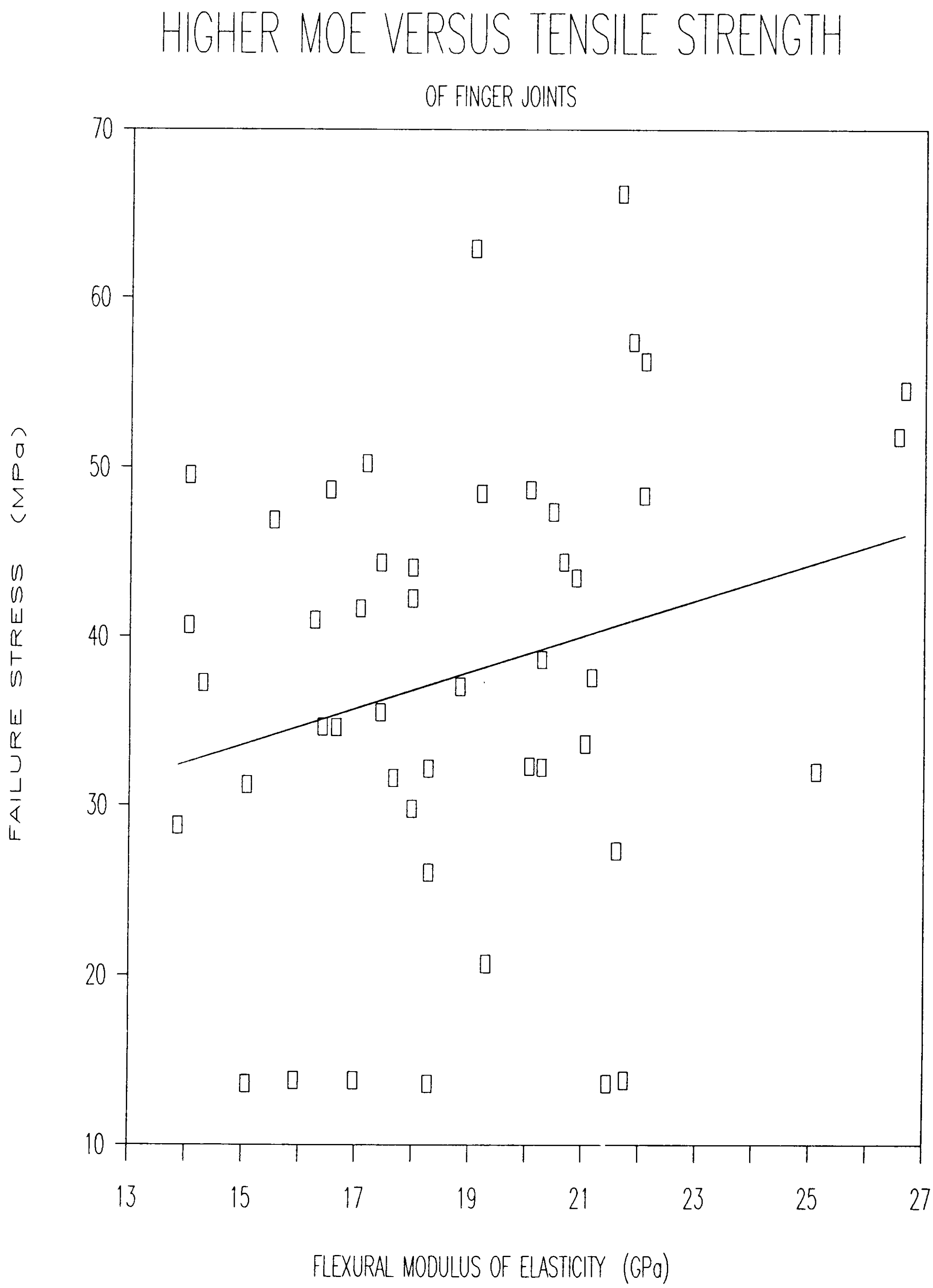

FIGURE 5.7 SIMPLE LINEAR REGRESSION OF TENSILE STRENGTH OF FULL SIZED EUCALYPTUS GRANDIS FINGER JOINTS VERSUS MODULUS OF ELASTICITY OF THE STIFFER BOARD.

6. ESTIMATING THE STRENGTH OF FINGER JOINTED TENSILE MEMBERS

6.1 INTRODUCTION

It has always been assumed that the permissible strength of lower grade timber boards can be improved by the removal of natural strength reducing features such as knots and slope of grain and by replacing these with finger joints. It is generally accepted that the strength of finger joints in visually clear timber is usually better than the strength of the timber with the permitted strength reducing features. Burdzik *et al*[6.10] have found that in the case of laminated *E. grandis* beams failure is generally initiated at the finger joints in the outer tension laminates. Natterer[6.11] confirmed that it was also their experience that failure of laminated spruce beams occurred at the finger joints in the tensile zones of the members. This seems to indicate that finger joints, that are generally placed in zones of fairly high grain distortion, are the biggest strength reducing features in the laminates. To make matters worse, no limit has been placed on the number of finger joints in a board. When a board, with more than one finger joint, is used as a tension member, the weakest link theory applies.

Multiple laminated *E grandis* boards are used as tension members in South Africa. Two to three boards are laminated together to obtain stocky flexural, compression and tension members. These are used in trusses and connections are effected by means of nail plates so that eccentric joints are avoided. A similar type of laminated purlin is used and this allows the manufacturer to place his purlins and trusses at large centres. Large distances can be spanned in this way with the result that long tension members are found in the trusses.

From the above it is clear that a number of important factors are not addressed in the South African Timber Design Code[6.7]. The factors that could be important are:

i) The number of finger joints in a tensile member.

ii) The effect of laminating tensile members.

It is the author's opinion that these shortcomings can best be investigated by means of computer simulation. In the following paragraphs the simulation method is described and used to investigate the effect of the number of finger joints in a single laminate tensile member. The simulation method is then expanded to investigate the strength of two laminate tensile members, without finger joints and then with finger joints.

6.2 THEORETICAL METHODS USED IN THE SIMULATION

Any simulation of finger joint strength should have a distribution similar to that on which the finger joint strength is based. One must bear in mind that any mathematical model has shortcomings, and that these must be taken into account when evaluating the results. Finger joint strength, based on the evaluation of laboratory tests, was assumed to be normally distributed. (See Figure 5.3 and paragraph 5.4) In order to simulate natural variation in the strength of finger joints, a method is required that will calculate normally distributed variants to the given strength value.

The method as described by Box *et al* in the book by Knuth[6.4], called the polar method for normal variants, has been applied. To find normalized variants to a value of finger joint strength the following formula was used:

$$f' = f_0 + \text{Std Dev of } f \times (\sqrt{-2 \times \ln(r_1)}) \times (\cos(2 \times \pi \times r_2))$$

where: r_1 and r_2 are uniformly distributed pseudo-random numbers that lie between zero and one,

$(\sqrt{-2 \times \ln(r_1)}) \times (\cos(2 \times \pi \times r_2))$ is the normally distributed random number with values between minus infinity and plus infinity,

f' is the normally distributed variant of finger joint strength f_0 and

f_0 is the mean value of the finger joint strength.

The method described above could give negative finger joint strengths. Finger joint strengths, however, can never be negative. *"In order to reconcile these apparent contradictions, it must be pointed out that the assumption of a random variable having a normal distribution is simply an assumption regarding the form of the mathematical model which, at best, is just an approximation to the real situation."* (See Ref 6.2)

Uniformly distributed pseudo random numbers were obtained by using the subroutine that is available in Turbo Pascal[6.1] and uniformly distributed finger joint strengths were obtained using the method given above. The mean finger joint strength and standard deviation were obtained from test values, the results of which are given in Chapter 5.

The method described above was tested to ascertain whether the results obtained from finger joint strength simulation would be acceptable. A mean strength for the finger joints, in *E. grandis* boards, of 36,4 MPa and a standard deviation of 9,0 MPa were used for the simulation. Five hundred replications of the simulation were obtained and the distribution of the values are shown in Figure 6.1. The mean simulated finger joint strength was 36,9 MPa and the standard deviation 10,3 MPa. As the results from the simulation and test results are very similar it was decided that this method would be used in all further simulations, be they for strength, length or modulus of elasticity.

6.3 MEMBER TYPES TO BE SIMULATED

Two types of tensile members can be found and the strength simulation of these will differ.

i) The most common type of tension member is a member that is made up of single boards that are joined in their length by means of finger joints. The individual boards that make up the member may vary in length. As the individual boards vary in length so will the number of finger joints in that member vary. Finger joint strengths and individual board lengths will be assumed to have a normal distribution.

ii) Of late the multiple laminated tension members have been used in South Africa. Individual boards are connected by means of finger joints and these are then laminated. Two and three laminate thicknesses are generally used. The simulation of this type of tension member differs from the previous because of the interaction between the two laminates.

Failure of a finger joint in a two laminate member will cause changes in the stress flow direction. The tensile force in the failed laminate must be transferred by means of shear as well as tensile stress perpendicular to the grain. Failure would occur due to crack propagation and this would lead to delamination of the failed laminate.

A failed finger joint in a laminate of a tension member is equivalent to a butt joint in that laminate. Leicester[6.5] has shown that the ultimate stress that will cause crack propagation in or between the laminates of a beam with an edge butt joint can be given by:

$$f_{t(ult)} = \frac{0,15 \text{ x density}}{(\pi \text{ x } 2a)^{0,5}}$$

and that of an inner laminate with a butt joint by:

$$f_{t(ult)} = \frac{0,15 \times density}{(\pi \times a)^{0,5}}$$

Where: $f_{t(ult)}$ is the ultimate stress in MPa
density in kg/m^3
a is the thickness of the laminate in mm

If these formulas are applied to the *E. grandis* used in this study and a high value of 800 kg/m^3 for the density is used, the ultimate strength of a laminate with an edge butt joint would be 10,2 MPa and that of an inner laminate with a butt joint, 14,4 MPa. Both these values are very low and indicate that in most cases delamination of the failed laminate will occur.

Failure of any finger joint in an outer laminate of a three laminate tension member will lead to failure as crack propagation and delamination of the failed laminate can be expected. Failure of a finger joint in an inner laminate would, in most cases, lead to failure along the faces of the failed laminate due to crack propagation. This would lead to an increase in stress over the whole length of the remaining two laminates.

6.4 FACTORS AFFECTING THE SIMULATION.

The computer model must copy the manufacturing procedure and assume that boards are connected by means of finger joints that have a normal or log-normal distribution of strength. It will be assumed that board lengths can be either normally distributed or have random lengths between certain limits. Position of the finger joints will be determined by the length of the individual boards.

Finger jointing of individual boards is a continuous process and final member lengths are obtained by cross cutting the long board. Where lamination of the boards is to take place, the length of the member is governed by the length of the lamination bed. Where the board is to be used as a single member, as opposed to a laminated member, it will be assumed that the boards are cut to length. Laminated tension members can, however, be cut into shorter lengths. Simulation of such members must take these factors into account and assumptions will be made about the storage or handling length.

6.5 SINGLE *E. GRANDIS* BOARD TENSILE MEMBERS

6.5.1 SIMULATION RESULTS.

Various simulations of single tensile members with finger joints were undertaken to determine the effects of individual board length and the coefficient of variation in board length on the strength of the member. The member length was kept at 6 m and the individual board length as well as the coefficient of variation of the length were varied. Results of the simulations are given in Table 6.1 and the distribution of the strength of the first simulation is given in Figure 6.2. Finger joints were assumed to have a mean tensile strength of 36,4 MPa with a standard deviation of 9,0 MPa. The strength of the timber between the finger joints was not considered as it was felt that the finger joints would in most cases be weaker than the timber.

Member length mm	Board length mm	Coeff of Var. length %	Avg Strength MPa	Std Dev MPa	Perm Str MPa
6000	3000	10	29,57	8,31	7,14
6000	2000	10	27,31	9,48	5,26
6000	1000	10	23,31	6,67	5,54
6000	3000	50	31,06	9,58	7,11
6000	3000	33,3	30,34	9,92	6,29
6000	3000	16,6	32,24	9,33	7,58

Table 6.1: Simulated strength of finger jointed *E. grandis* tensile members.

6.5.2 DISCUSSION.

The first three cases of Table 6.1 show that the strength of a single finger jointed tensile member is very sensitive to the number of finger joints that can appear in the member. A member that has only one finger joint should have a mean strength of 36,4 MPa. The first case shown above will have tensile members with more than one finger joint. This lowers the mean tensile strength to 29,57 MPa. The permissible strength based on the method described in SABS 0163[6.7] would be 7,14 MPa. This value is slightly less than the 7,4 MPa given in SABS 0163. In the case where up to six finger joints can be found as in case three above the mean strength drops to 23,31 MPa and the permissible stress to 5,54 MPa.

The second three cases in Table 6.1 show that the permissible strength of the finger jointed tensile member is fairly insensitive to the variation in the coefficient of variation in length of the individual boards that make up the member. Case four would give a permissible stress of 7,11 MPa, case five 6,29 MPa and case six 7,58 MPa. The average for the three is about 7,0 MPa, which is in keeping with the value obtained for the first case. Another simulation may give slightly different results but the general trends would be the same.

Further simulations were carried out to study what the effects the coefficient of variation and the number of finger joints would have on the strength of a finger jointed tensile member. Figure 6.3 shows how the permissible stress of finger jointed boards varies with the number of finger joints as well as with the coefficient of variation of the finger joint strength. Simple regression lines are fitted and these vary from a linear with a high correlation coefficient, for finger joints with a 10% coefficient of variation, to a multiplicative with a high correlation coefficient, for finger joints with a 40% coefficient of variation. Between the two is a transitional zone with a lower correlation coefficient. The correlation coefficient for the 10% variation is 0,991 and for the 40% variation 0,982.

From the above simulation it is obvious that some limit should be placed either on the number of finger joints that may appear in a tensile member and/or the coefficient of variation of the finger joints. Together with these limitations a stress reduction factor must be given to allow the designer to calculate a safe design stress. This stress reduction factor must not only take the coefficient of variation of the finger joints into account but also the number of finger joints. Suggested formulas for permissible stress are:

For : 10% variation Perm stress = $(0{,}373 - 0{,}00626 \times n) \times$ Mean strength

20% variation Perm stress = $(0{,}303 - 0{,}0129 \times n) \times$ Mean strength

30% variation Perm stress = $(0{,}210 \times n^{-0{,}285}) \times$ Mean strength

40% variation Perm stress = $(0{,}175 \times n^{-1{,}084}) \times$ Mean strength

where: n = No of finger joints
% variation is % coefficient of variation in finger joint strength

It can be seen from Figure 6.3 that high variability in the strength of the finger joints will lead to very low permissible strengths for the finger joints. It would pay the manufacturer to seek methods of lowering the variability of the finger joint strength of tensile members. A 10% coefficient of variation in finger joint strength will give permissible strengths that are twice those of finger joints with a coefficient of variation of 30%. The author estimates that the strength of finger joints in South African *E grandis*, glued with p.r.f., has a coefficient of variation of about 25%. This leads to fairly low permissible stresses for tensile members having three or more finger joints, i.e. 7,6 MPa for three finger joints and 6.76 MPa for five finger joints.

If the coefficient of variation could be dropped to 20%, the permissible strength for tensile members with three and four finger joints would be 9,7 MPa and 9,2 MPa respectively. These values are in keeping with the tensile strength found in Chapter 4, where a permissible stress for E grandis with defects, of 9,6 MPa is suggested. Up to four finger joints in a tensile member would not decrease the permissible stress significantly if the coefficient of variation of the strength of the finger joints could be kept below 20%.

6.6 LAMINATED TENSILE MEMBERS.

Short laminated tensile members that are made up of two laminates can have either no finger joints at all or a finger joint in one or both of the two laminates. Bearing in mind that the modulus of elasticity of the two elements of the members will be different and that the deformation of the two elements will be the same, the stress levels in the two members will be different. Taking the relative stiffness of the laminates into account, failure of a two laminate tensile member can occur in one of three ways.

i) No Finger joints — Failure will occur when the weakest element of the member fails at a defect. The ultimate load that the member can carry will be equal to the force required to initiate failure in the weaker laminate plus the proportion of the load carried by the second laminate. In the rare case where one of the laminates is very much stronger than the other, the ultimate tensile load could be equal to the failure stress of the stronger laminate multiplied by the area of that laminate.

ii)	Finger joint/joints in one of the laminates	The failure load of the tensile member is the minimum of either the failure load of the finger joint plus the portion of the load carried by the second laminate or the failure of the unjoined laminate plus the proportion of the load carried by the joined laminate.
ii)	Finger joint/joints in both laminates	The failure load of the tensile member is the failure load of the weaker finger joint plus the proportion of the load carried by the second laminate at the section of the weaker finger joint.

Longer members will be more inclined to have a finger joint in each of the laminates. As mentioned previously, failure of a finger joint will cause delamination of the failed laminate. Strength of the member will be dependent on the tensile strength of the weakest finger joint in the whole member.

The stress in the laminates can be given by the following formula.

$$\frac{f_1}{E_1} = \frac{f_2}{E_2}$$

where: f_1 is the stress in laminate 1
f_2 is the stress in laminate 2
E_1 is the modulus of elasticity of laminate 1
E_2 is the modulus of elasticity of laminate 2

The modulus of elasticity and the tensile strength of the laminate may be positively correlated. Figure 2.3 shows the correlation between modulus of elasticity and tensile strength for South African *E grandis*. A correlation coefficient of 0,55 was obtained. The correlation between finger joint strength and modulus of elasticity was found to be very low and a value of 0,32 was obtained in Section 5 (see Figure 5.6).

The simulation program should take the correlation between tensile strength and modulus of elasticity, finger joint strength and modulus of elasticity and between tensile strength and finger joint strength into account. These values appear to be positively correlated and will be treated as such.

6.7 SIMPLIFIED SIMULATION MODEL FOR TWO LAMINATE TENSILE MEMBERS.

6.7.1 ASSUMPTIONS USED IN THE SIMPLIFIED SIMULATION MODEL.

The simplified model assumes that the strength of the timber, strength of the finger joint and the modulus of elasticity are not positively correlated and are random values. The model goes further in that the relative stiffness of the boards is ignored and that the stress is uniformly distributed over the total area.

6.7.2 INPUT VALUES FOR SIMPLIFIED SIMULATION.

A limited number of simulations were undertaken to see whether a simplified model would work as well as the more complex model, in which the correlation between strength and modulus of elasticity as well as the relative stiffness of the laminates are taken into account. The mean strength and the standard deviation for the strength of the timber was taken as being 55,6 MPa and 21,3 MPa respectively, these being the values obtained from laboratory tests on boards having defects smaller than 27% of the cross-sectional area. (See Chapter 2) The tensile strength of the boards was assumed to have a log-normal distribution. Finger joint strengths were obtained from the work done by van Rensburg et al[6.8] and the mean and standard deviation were 36,4 MPa and 9,0 MPa respectively.

A cut length of 1 m for the tensile member was assumed while the individual board lengths varied from 1 m to 3 m in steps of 0,5 m. A coefficient of variation of 20% was assumed for the board length for all five cases. Two hundred replications of each configuration were analysed and the maximum strength for each replication determined. Figure 6.4 shows the distribution of strength for the 1,5 m long boards.

6.7.3 RESULTS OF SIMPLIFIED SIMULATION.

The mean and standard deviation as well as the permissible stress, using the method described by Simon[6.6], of each case were calculated and are given in the Table 6.2 below. The minimum number of finger joints that occurred are given. A value of 2 for the finger joints means that there was at least one finger joint in each laminate, 1 at least one finger joint in one of the two laminates and 0 no finger joints in the member.

Board length	Finger joints %			Mean	Std Dev	Perm
mm	2	1	0	MPa	MPa	MPa
1000	83	17	0	30,72	8,04	8,13
1500	39	54	7	33,68	10,33	8,64
2000	21	56	23	36,14	11,55	9,32
2500	19	44	37	37,72	11,17	9,98
3000	7	54	39	39,66	13,64	9,56

Table 6.1 : RESULTS OF SIMPLIFIED SIMULATION OF TWO LAMINATE TENSILE MEMBER 1 m LONG

A permissible stress of 9,71 MPa for finger joints in tension was found in Chapter 5 and a permissible stress of 11,9 MPa for the E grandis boards in Chapter 4. Where the board lengths are short the strength of the finger joints predominates and where the boards are long the strength of the timber predominates. The above results show that as the number of finger joints decreases the permissible stress increases and tends towards the permissible stress of the boards. However, as the number of finger joints in a member decreases the coefficient of variation will increase which can result in a decrease in strength.

6.8 SIMULATION USING POSITIVELY CORRELATED VALUES.

6.8.1 DESCRIPTION OF METHOD USED.

A method is described by Hart[6.3] whereby positively correlated normally distributed random variables can be generated for use in a Monte Carlo analysis. Consider *n* correlated random variables (X_1, X_2, ... , X_n) with a joint probability density function. The PDF is defined if the means, variances and covariance of the random variables are known.

The mean vector can thus be described by:

$$\{X\} = \begin{vmatrix} X_1 \\ X_2 \\ . \\ . \\ X_n \end{vmatrix}$$

and the covariance matrix by:

$$[S_x] = \begin{vmatrix} Var(X_1) & Cov(X_1,X_2) & \ldots\ldots & Cov(X_1,X_n) \\ Cov(X_2,X_1) & Var(X_2) & \ldots\ldots & Cov(X_2,X_n) \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ Cov(X_n,X_1) & Cov(X_n,X_2) & \ldots\ldots & Var(X_n) \end{vmatrix}$$

If m random numbers for each variable need to be generated then the *j*th generated random number for the *i*th random variable is denoted as:

$$^{(j)}x_i \qquad j = 1,2,\ldots\ldots, m$$
$$i = 1,2,\ldots\ldots, n$$

The random number generation process starts by generating *n* sets of statistically independent normally distributed random numbers with a yet to be specified mean vector and covariance matrix. Each set has *m* random numbers. These random numbers are denoted as:

$$^{(j)}y_i \qquad j = 1,2,\ldots\ldots, m$$
$$i = 1,2,\ldots\ldots, n$$

A linear transformation is then defined which couples the *Y* random variables in such a way as to form the correlated *X* random variables. That is:

$$\underset{(nx1)}{\{^{(j)}x\}} = \underset{(nxn)}{[C]} \underset{(nx1)}{\{^{(j)}y\}}$$

If two sets of random variables are related by a linear transformation, e.g.

$$\{X\} = [C]\{Y\}$$

then

$$\{\overline{X}\} = [C]\{\overline{Y}\}$$

and

$$[S_X] = [C][S_Y][C]^T$$

where $\{\overline{X}\},\{\overline{Y}\}$ = mean vectors

$[S_X],[S_Y]$ = covariance matrices

Here $\{X\}$ and $[S_X]$ have the properties of the random variables one wishes to generate and are therefore known. $[C]$, $\{Y\}$, and $[S_Y]$ must be found so that sets of normal random numbers, $^{(j)}y_k$, can be transformed by using the above equations into sets of correlated normal random numbers, $^{(j)}x_i$, with their mean vector and covariance matrix given by $\{X\}$ and $[S_X]$, respectively. These matrices are found by using the Choleski decomposition method.

The method states that a symmetric matrix of order $n \times n$, denoted [A], can be decomposed into the matrix product:

$$[A] = [V][D][V]^T$$

$[V]$ is a lower triangular triangular matrix of order $n \times n$ with ones on the principal diagonal, and $[D]$ is a diagonal matrix of order n.

By inspection of the above equations it can be seen that:

$$[A] = [S_X]$$
$$[C] = [V] \quad \textit{(lower triangular matrix)}$$
$$[S_Y] = [D] \quad \textit{(diagonal matrix)}$$

The appropriate linear transformation matrix $[C]$ and the covariance matrix $[S_Y]$ are now defined.

6.8.2 CORRELATED VALUES USED IN SIMULATION OF TENSILE MEMBERS.

The following values were obtained from laboratory tests (See van Rensburg *et al*[6.8] and Section 2):

Function	Mean	Std Dev
	MPa	MPa
Modulus of elasticity (E)	15230,0	3200,0
Tensile strength timber (T)	55,6	21,3
Finger joint strength (F)	36,4	9,0

Table 6.2 : STRENGTH PROPERTIES FROM TEST RESULTS

The values of the functions were all converted to the natural logarithm of the values as a log-normal curve seemed to fit the distribution of the modulus of elasticity and of the strength of the timber. To use the method described above, the strength of the finger joints was also assumed to have a log-normal distribution. Values used for the simulation are tabulated below:

Function	Mean	Std Dev
Modulus of elasticity (E)	2,703	0,200
Tensile strength timber (T)	3,942	0,405
Finger joint strength (F)	3,560	0,265

The correlation coefficients between the various functions are:

Between: E and T = 0,524
T and F = 0,7 **(Estimated)**
F and E = 0,334

The covariances between the different functions can be calculated:

Cov(E,T) = 0,524 x 0,1997 x 0,4053 = 4,212E-2
Cov(E,F) = 0,334 x 0,1997 x 0,2652 = 1,772E-2
Cov(T,F) = 0,7 x 0,4053 x 0,2652 = 7,033E-2

The covariance matrix can then be written with the following values:

S_X =

3,9886E-2	4,2412E-2	1,7722E-2
4,2412E-2	1,6427E-1	7,5241E-2
1,7722E-2	7,5241E-2	7,0336E-2

Using the method described above the following matrices result:

C =

1,0000	0,0000	0,0000
1,0633	1,0000	0,0000
0,4443	0,4733	1,0000

$$D = \begin{array}{c|c|c} 0,03989 & 0 & 0 \\ \hline 0 & 0,1192 & 0 \\ \hline 0 & 0 & 0,01736 \end{array}$$

The mean vector equations can thus be written:

$$\begin{vmatrix} 2,7031 \\ 3,9425 \\ 3,5607 \end{vmatrix} = \begin{vmatrix} 1,0000 & 0 & 0 \\ 1,0633 & 1,0000 & 0 \\ 0,4443 & 0,4733 & 1,0000 \end{vmatrix} \begin{vmatrix} Y_1 \\ Y_2 \\ Y_3 \end{vmatrix}$$

From the equation above the values of the {Y} vector can be obtained and from the [D] matrix the values of the standard deviations of the Y values.

Function	Mean	Std Dev
Y1	2,7031	0,1997
Y2	1,0683	0,3452
Y3	1,8541	0,1318

These values will be used in the simulation to generate positively correlated normally distributed values for modulus of elasticity, tensile strength of the timber and finger joint strengths.

6.8.3 SIMULATED VALUES.

Simulation of the modulus of elasticity, tensile strength of the timber and finger joint strength, using the values above resulted in the following tabulated values. The values given are based on four hundred replications and the distribution of these values is shown in the Figure 6.5 to Figure 6.9.

Function	Mean MPa	Std Dev MPa
Modulus of elasticity	15300,00	3230,00
Strength of the timber	58,51	26,74
Finger joint strength	36,59	8,77

Table 6.3 : STRENGTH PROPERTIES OBTAINED FROM COMPUTER SIMULATION

The values of the strength properties as calculated in the simulation and presented in Table 6.3 can be compared to the values of the properties as obtain from test results and presented in Table 6.2. The correlation coefficients were also calculated and are given below.

Between:	E and T	= 0,573
	T and F	= 0,810
	F and E	= 0,440

The simulated values as well as the correlation between the simulated functions are such that the method described as well as the values above were used to simulate various double laminated tensile member configurations.

6.9 SIMULATION OF TWO AND THREE LAMINATED MEMBERS WITHOUT FINGER JOINTS.

6.9.1 INTRODUCTION.

It is commonly believed that when two or more timber members are used to share a common load the permissible stress for the two or more members is greater than the permissible stress for one member only as it is assumed that the members will not be equally strong or stiff. The stiffer member, which is also presumed to be the stronger member, will carry a greater portion of the load, so relieving the less stiff and hence weaker member. This may be true in cases where the increase in stiffness leads to a large increase in strength. Where a large increase in the stiffness leads to a moderate increase in strength, as in the case of South African *E. grandis*, this may no longer be true. The two laminate member strength will be governed by the weakest laminate and if this laminate is also the stiffer laminate, it will in fact be weakened still further. CP 112[6.9] only allows an increase in permissible stress where four and more members share a load. SABS 0163[6.7] makes no mention of the number of members that share the load.

6.9.2 SIMULATIONS UNDERTAKEN.

To determine whether load sharing between members having different stiffness takes place and whether this has a strengthening effect, two and three laminate tension members without finger joints were simulated. It was assumed that strength and modulus of elasticity of the boards had the values as found in Chapter 2. Three hundred replications of the two laminate member simulation were undertaken and the results show that the mean tensile strength was lower than the mean strength for the individual boards. Instead of showing an increase in strength, as could assumed from the South African timber design code, SABS 0163[6.7], paragraph 5.3.4, the permissible stress showed a decrease as given in Table 6.3. The percentage decrease in permissible stress is 28 % instead of an increase of 15 % as permitted by the code. Although the permissible stress for a two laminate tensile *E. grandis* member is higher than the permissible stress given in SABS 0163[6.7] the simulation shows that an increase in permissible stress for bending should not be allowed and that a two laminate tensile member does not have a higher permissible stress than a single laminate tensile member.

To ascertain whether a three laminate tension member showed the same decrease in permissible stress, 200 replications of the three laminate were undertaken and the results are given in Table 6.3. The simulations show that the three laminate tensile member has a lower permissible stress than the single laminate *E. grandis* tensile member. Although the mean stress of the two laminate member is higher than that of the three laminate member the variability of the strength decreases with the number of laminates thus leading to an increase in the permissible stress.

Number of laminates	Mean MPa	Std Dev MPa	Perm MPa
One	55,60	17,69	11,90
Two	44,83	15,60	8,60
Three	39,30	10,82	9,66

Table 6.4 : COMPARISON BETWEEN A SINGLE TENSILE LAMINATE STRENGTH AND SIMULATED TWO AND THREE LAMINATE TENSILE MEMBER STRENGTH

To ascertain whether the decrease in strength of a two laminate tensile member was as a result of the fairly weak correlation between tensile strength and modulus of elasticity, further simulations were undertaken wherein the correlation coefficient between modulus of elasticity and strength was varied between zero and unity in steps of 0,2. The permissible tensile stress for these simulations varied between 10,0 MPa for the zero correlation coefficient and 12,2 MPa for the unity correlation coefficient.(See Figure 6.10) Even when the correlation coefficient between modulus of elasticity and tensile strength is unity only a negligible increase in tensile strength can be expected for a double laminated member versus a single board.

6.9.3 DISCUSSION.

The assumption that the permissible stress of a two member load sharing structural element is 15 % higher (SABS 0163[6.7]) than that of a single element is not necessarily true for all timber genera and especially not for the South African *E grandis* boards that were tested. The ability of the stiffer member to carry the greater portion of the load depends on the slope of the tensile strength versus modulus of elasticity graph and its intercept with the tensile strength axis as well as the correlation between modulus of elasticity and strength. The steeper the graph becomes the greater the improvement should become. Whether this improvement would ever be as high as 15 % for the structural timber available in South Africa is an open question. Further testing of load sharing structural timber elements is required to validate the 15 % increase allowed by the code SABS 0163.

6.10 SIMULATION OF TWO LAMINATE TENSILE MEMBERS WITH FINGER JOINTS.

6.10.1 INTRODUCTION.

To ascertain whether the simplified model was inferior to the method using positively correlated values for strength, finger joint strength and modulus of elasticity, a cut length of the double laminated tensile member of 1 m was assumed and the length of the individual boards varied as in Table 6.2 Log-normal distributions were assumed and the method described in 6.7 with all relevant coefficients was used. The results were based on two hundred replications of each board length variation.

6.10.2 RESULTS OF SIMULATION.

The mean, standard deviation and permissible stress for each board length simulation were calculated and are shown in Table 6.4 below. These values do not differ significantly from the values obtained by the simplified method. More repetitions of each case in the table below would show that the general trend is an upward trend as the number of finger joints in the tensile member is decreased. There is no real significant difference between a board length of 2 m and a board length of 3 m as the total number of members having no finger joints is about the same. The values in Table 6.5 can be compared to the values given in Table 6.1.

Board length mm	Mean MPa	Std Dev MPa	Perm MPa
1000	28,53	5,76	8,99
1500	32,29	9,03	9,20
2000	33,75	11,26	8,74
2500	36,57	14,28	8,90
3000	39,35	14,45	9,40

Table 6.5 : RESULTS OF SIMULATION OF TWO LAMINATE TENSILE MEMBER 1 m LONG USING POSITIVELY CORRELATED VALUES.

6.10.3 DISCUSSION.

The simplified method could be used as an indicator of a possible trend as multiple repetitions are fast and no information about the correlation between the various functions is required. This method could also be used by manufacturers who do not understand the statistics involved in the method that uses the correlation between the various functions. Once the possible trend has been established, the method that uses the correlated values can be used to clarify or corroborate the values that were found by the simplified method.

6.10.4 FURTHER SIMULATIONS USING THE CORRELATED VALUE METHOD.

Having ascertained the effect of board length on the tensile strength of short members it was felt that the effect of short boards on long members should be looked into. To this purpose the individual board length was maintained at 1 m with a coefficient of variation of 20 % while the length of the tensile member was varied between 1 m and 6 m in steps of 1 m. The timber and finger joint properties were assumed to be log-normally distributed and were assigned the values as in paragraph 6.8. Five hundred replications of each simulation were undertaken and the mean, standard deviation and permissible stress were calculated according to the method described by Simon[6.6].

Cut Length mm	Mean MPa	Std Dev MPa	Perm MPa
1000	28,53	5,76	8,57
2000	25,66	4,44	8,26
3000	24,04	3,89	7,94
4000	23,37	3,32	8,06
5000	22,40	3,31	7,63
6000	22,05	2,99	7,71

Table 6.6 : RESULTS OF SIMULATION OF TWO LAMINATE TENSILE MEMBER OF VARYING LENGTH WITH BOARD LENGTH 1 m LONG USING POSITIVELY CORRELATED VALUES.

6.10.5 DISCUSSION.

As was expected, the mean strength of the tensile member became less as the number of finger joints and number of boards in the member increased (See Figure 6.11). Together with this loss in mean strength came a reduction in the standard deviation with the result that the permissible stress did not drop that dramatically. This reduction in the standard deviation can be expected as the strength of the tensile member is based on the weakest finger joint, which in the case of the 6 m long member can be up to 12 finger joint strength values. The more finger joint strength values that the weakest link is based on the narrower the distribution of these values will become and hence the smaller the value of the standard deviation.

6.11 CONCLUSION.

The important conclusions that can be drawn from this portion of the study can be seen as follows:

a) The number of finger joints in a single tension member is important as the permissible stress is reduced with an increase in the number of finger joints.

b) The variability of the finger joint strength in a single tension member is important as the permissible tensile stress decreases dramatically with an increase in the variability of the strength. In an effort to improve the strength of timber tension and flexural members, more effort should be spent on finding ways of decreasing the variability of the strength of the finger joint connections.

c) No increase in permissible stress could be discerned due to the load sharing effect of two tension members having a common load. In fact, a decrease in permissible stress was found. A permissible stress increase between three and two tension members sharing a common load was found due to the decrease in the variability of the strength of the three laminate tensile member. The factor for load sharing given in SABS 0163[6.7] Paragraph 5.3.4 in its present form should be removed from the code, or modified to exclude *E. grandis* and all laminated members, until tests have been done to validate it.

d) The loss in permissible stress for double laminated tension members that have a number of finger joints is less than expected, as a 6 m long member with an average of 10 finger joints still has a strength greater than that allowed by the South African timber design code SABS 0163[6.7]. Care should, however, be taken in very long tension members where the number of finger joints per side may be more than five.

e) Very little strength gain can be expected by manufacturers using double laminated, finger jointed tensile members as opposed to single, finger jointed tensile members. A two laminate, finger joint free member has a permissible stress that is slightly less than that of a single finger joint free board. In both cases the permissible stress is greater than that allowed in the South African timber design code SABS 0163[6.7].

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6.10 BURDZIK, W.M.G. and VAN RENSBURG, B.W.J., 1987. "The effect of finger-joint dispersion on the strength of laminated beams." South African Forestry Journal, No 141, June 1987, Pretoria

6.11 NATTERER, J., 1989. Private communication.

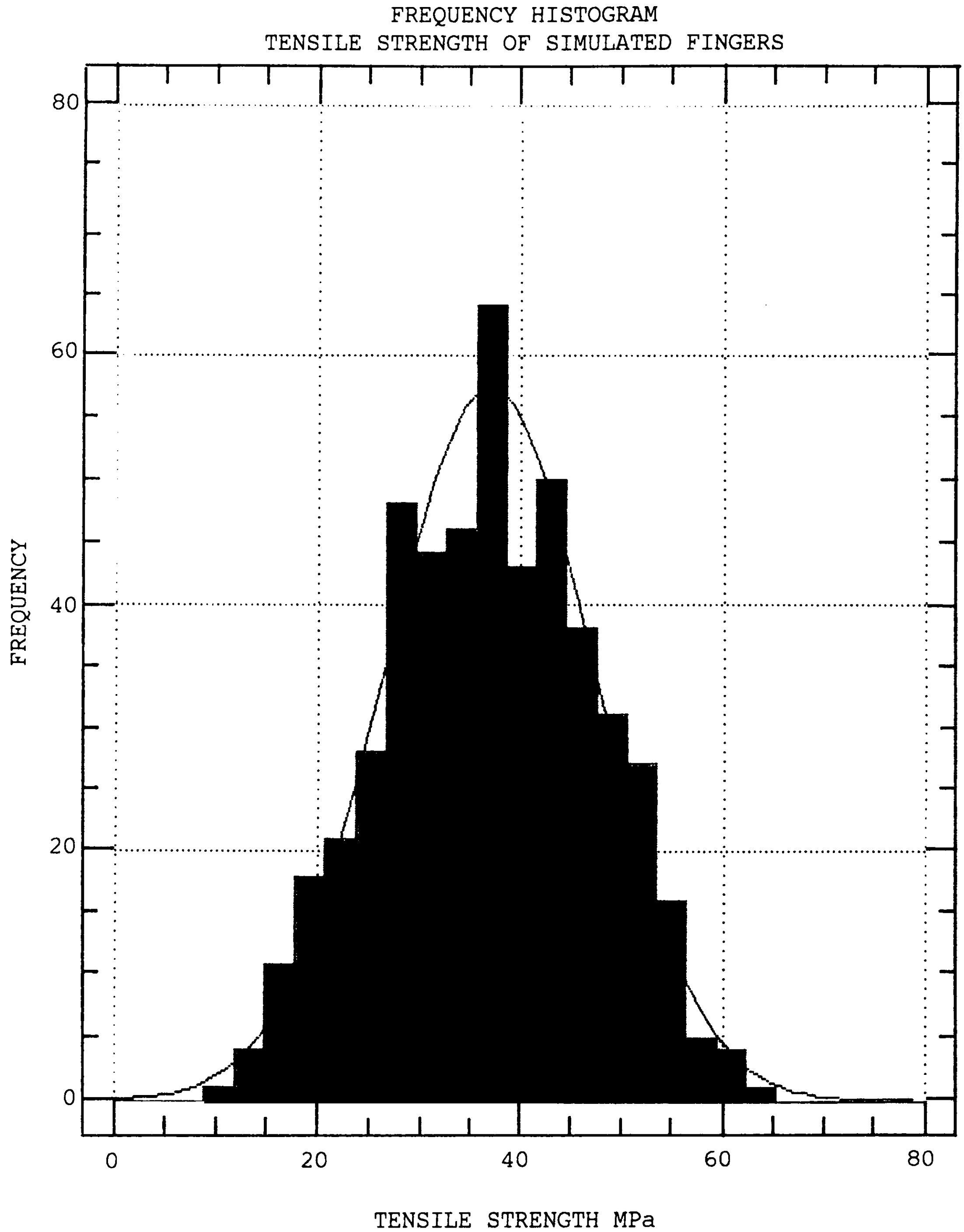

FIGURE 6.1 FREQUENCY HISTOGRAM OF SIMULATED FINGER JOINT STRENGTH.

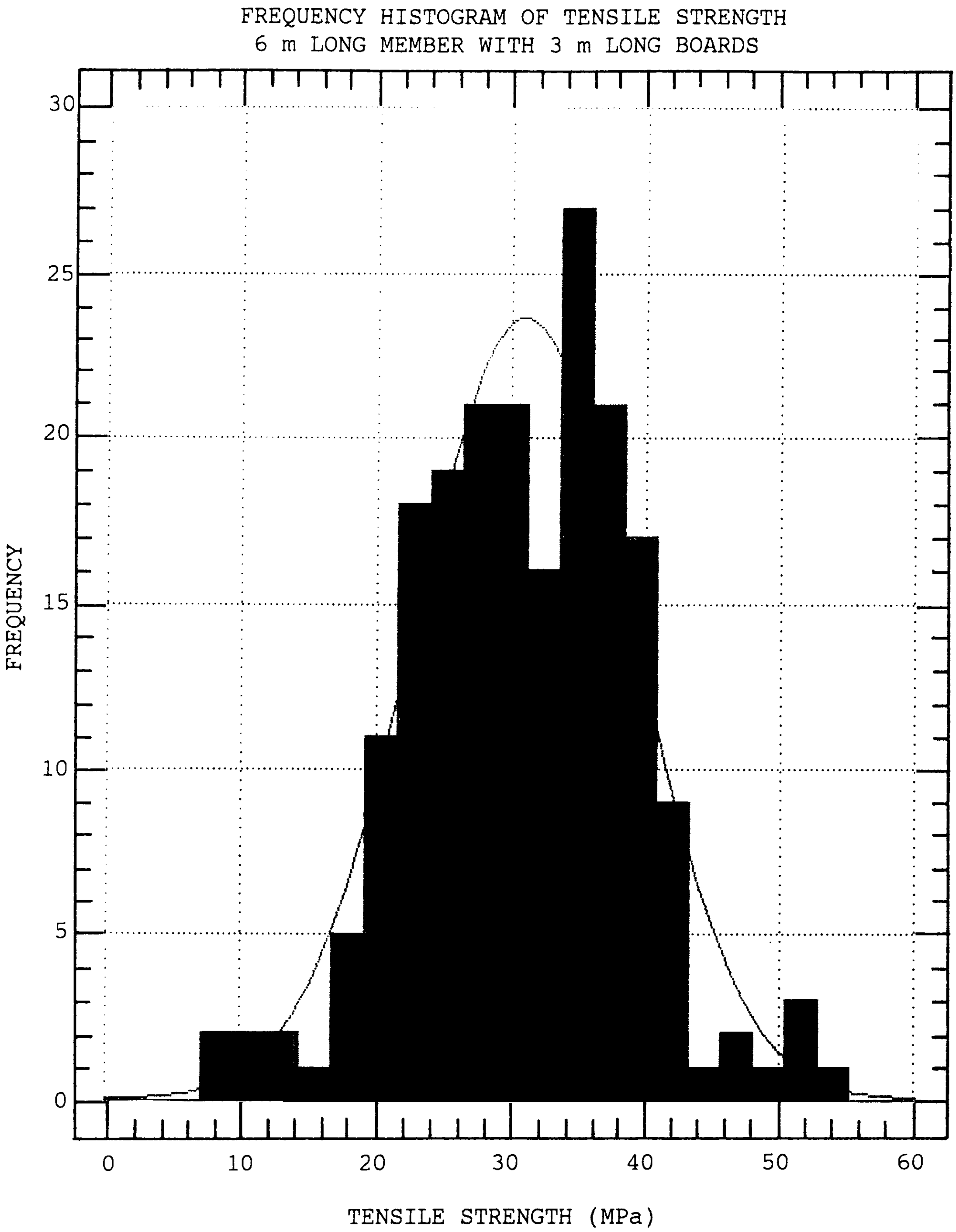

FIGURE 6.2 FREQUENCY HISTOGRAM OF TENSILE STRENGTH OF 6 m LONG MEMBER MADE UP OF 3 m LONG BOARDS WITH FINGER JOINTS.

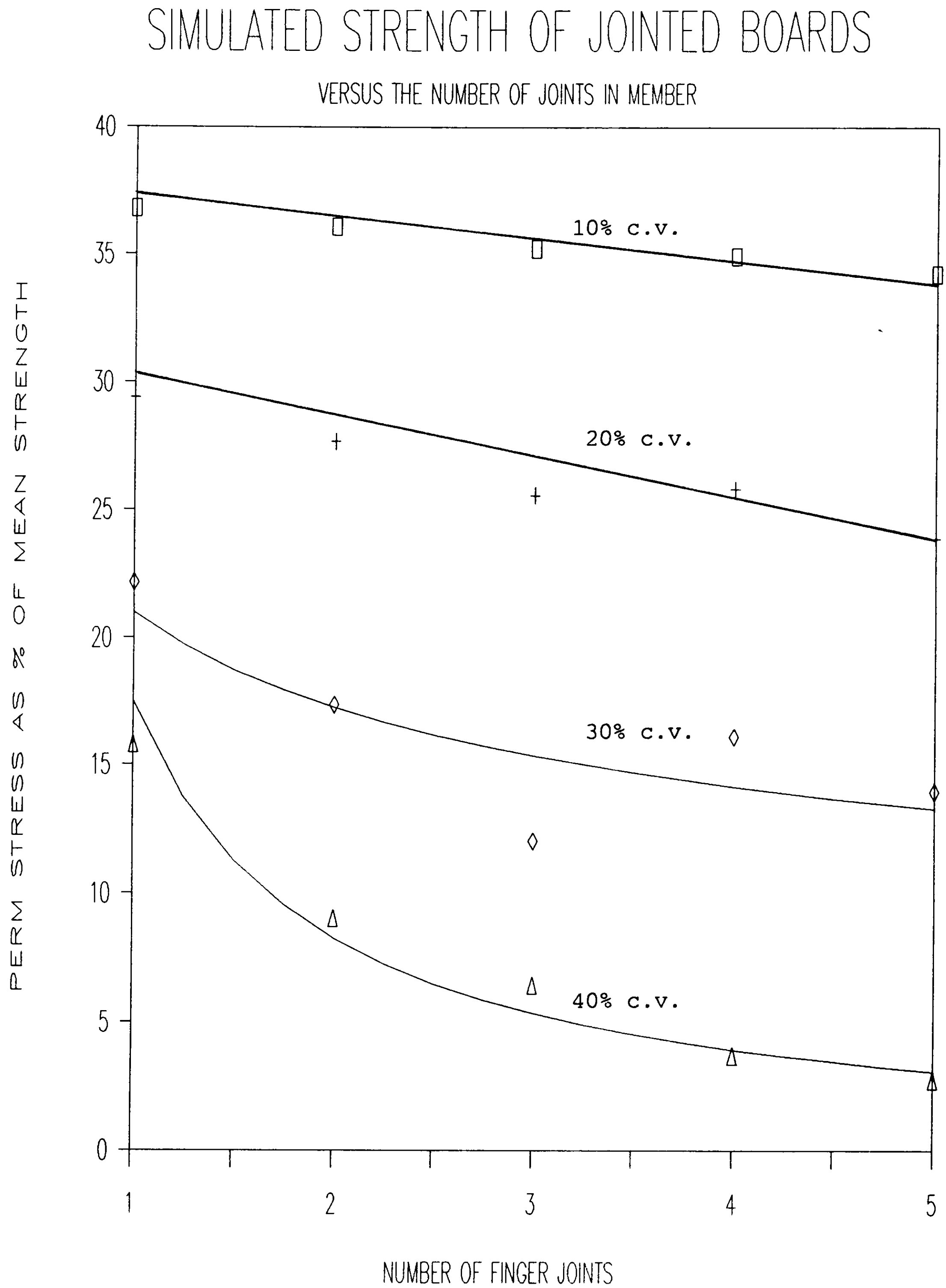

FIGURE 6.3 TENSILE STRENGTH OF FINGER JOINTED BOARDS FOR VARIOUS NUMBER OF FINGER JOINTS AND VARIOUS COEFFICIENTS OF VARIATION IN FINGER JOINT STRENGTH AS A FUNCTION OF THE MEAN STRENGTH OF THE FINGER JOINTS.

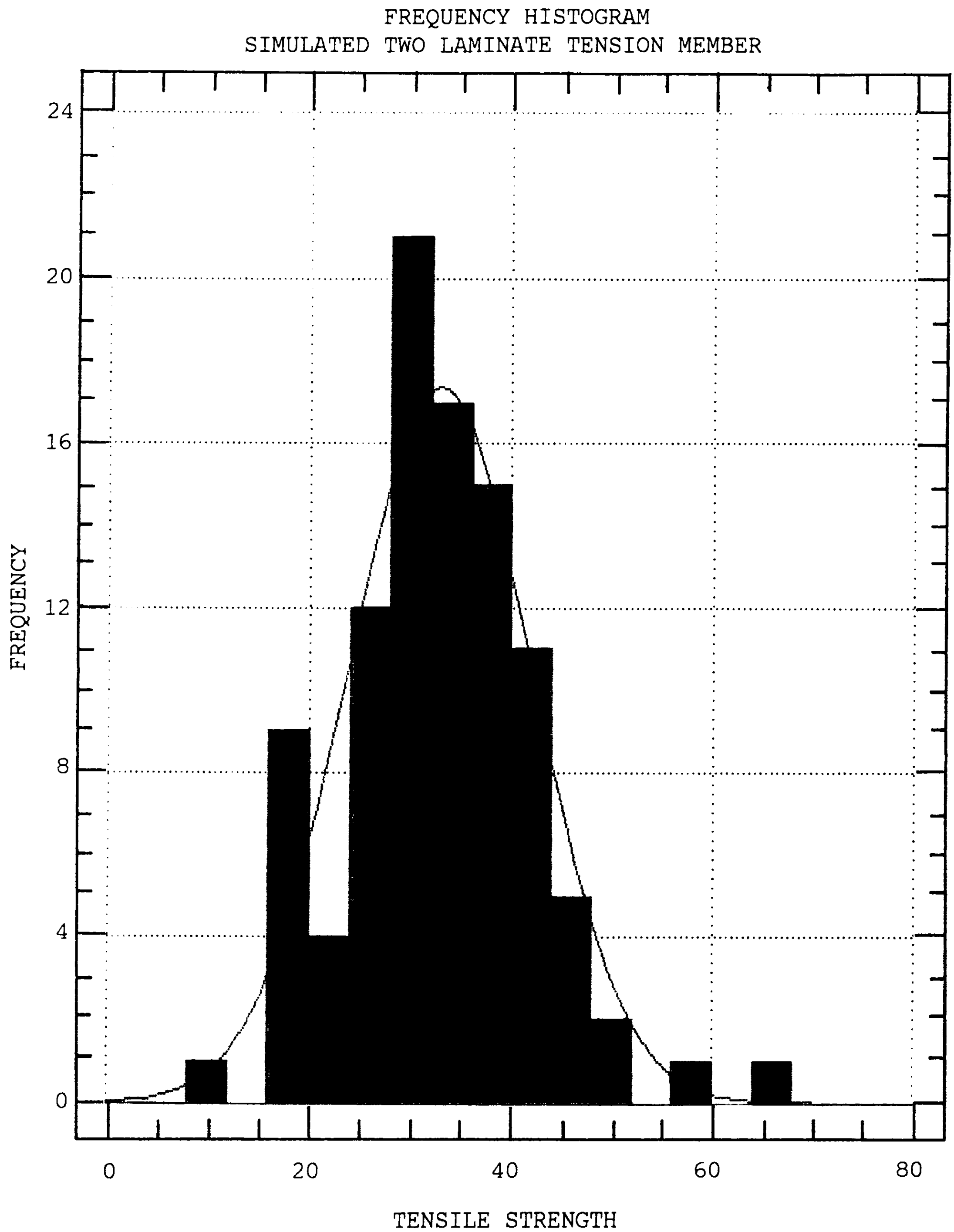

FIGURE 6.4 FREQUENCY HISTOGRAM OF SIMULATED DOUBLE LAMINATE TENSION MEMBER, 1 m LONG, MADE UP OF 1,5 m LONG BOARDS THAT ARE FINGER JOINTED.

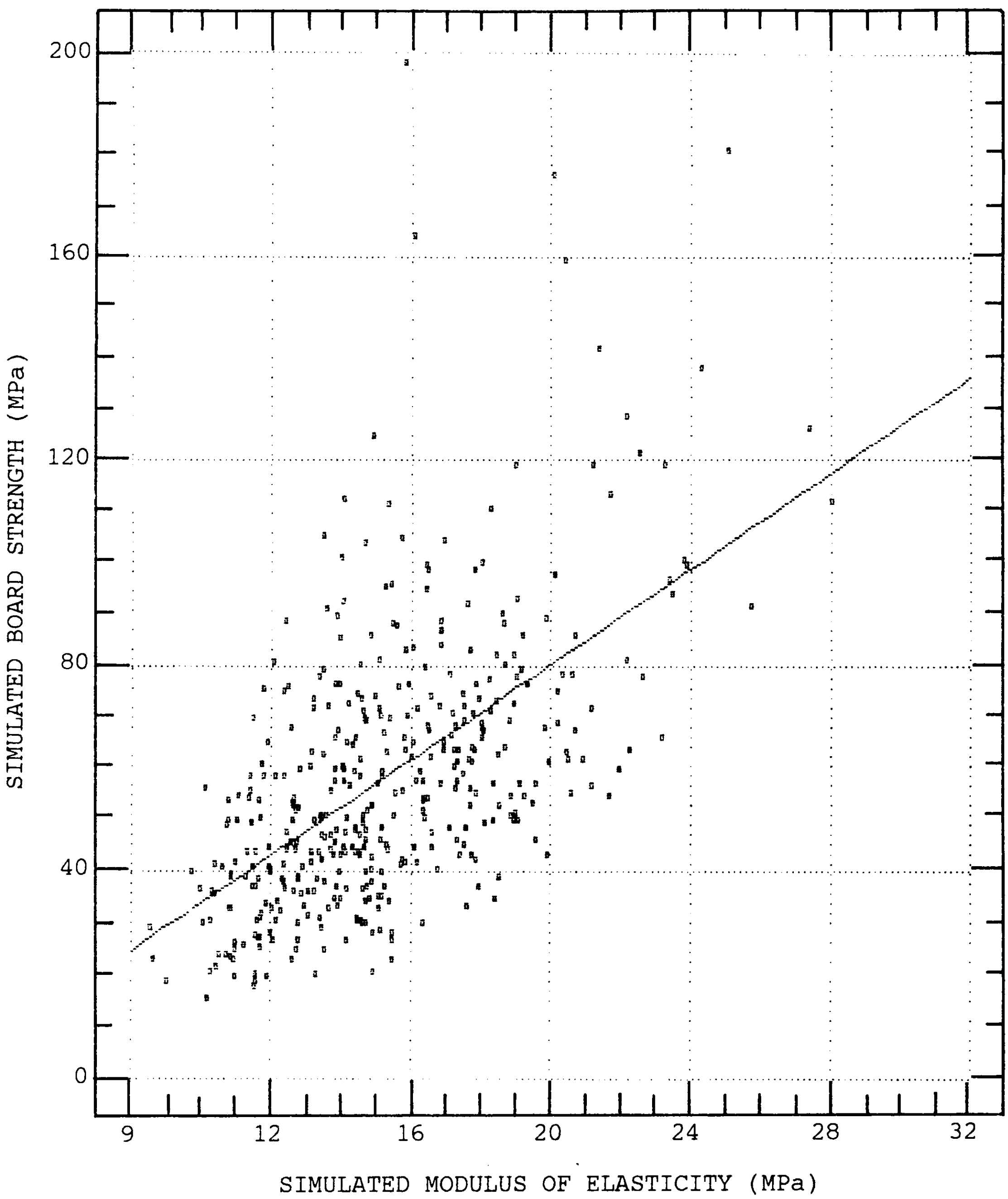

FIGURE 6.5 LINEAR REGRESSION OF SIMULATED BOARD STRENGTH VERSUS SIMULATED FLEXURAL MODULUS OF ELASTICITY.

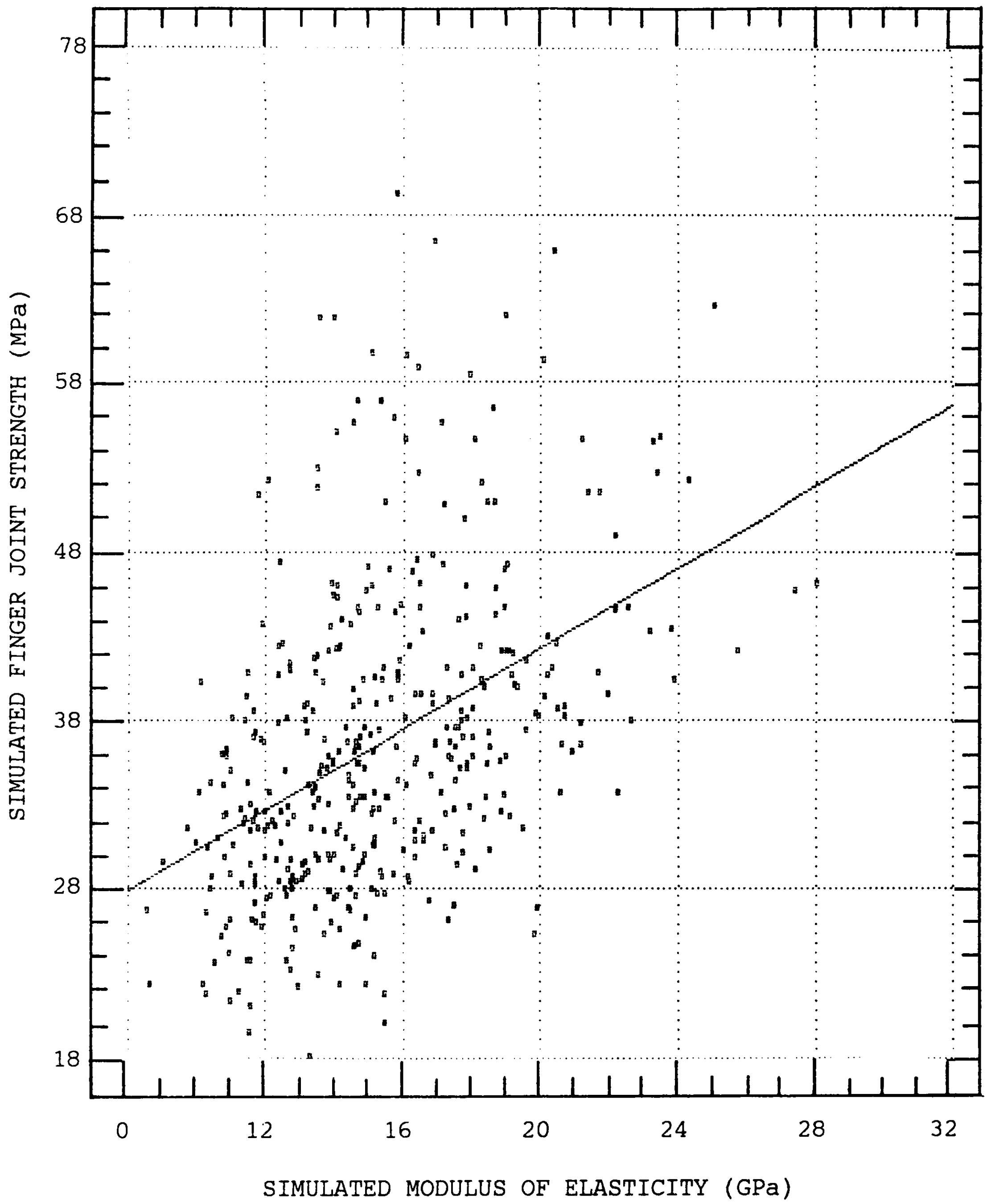

FIGURE 6.6 LINEAR REGRESSION OF SIMULATED FINGER JOINT STRENGTH VERSUS SIMULATED FLEXURAL MODULUS OF ELASTICITY.

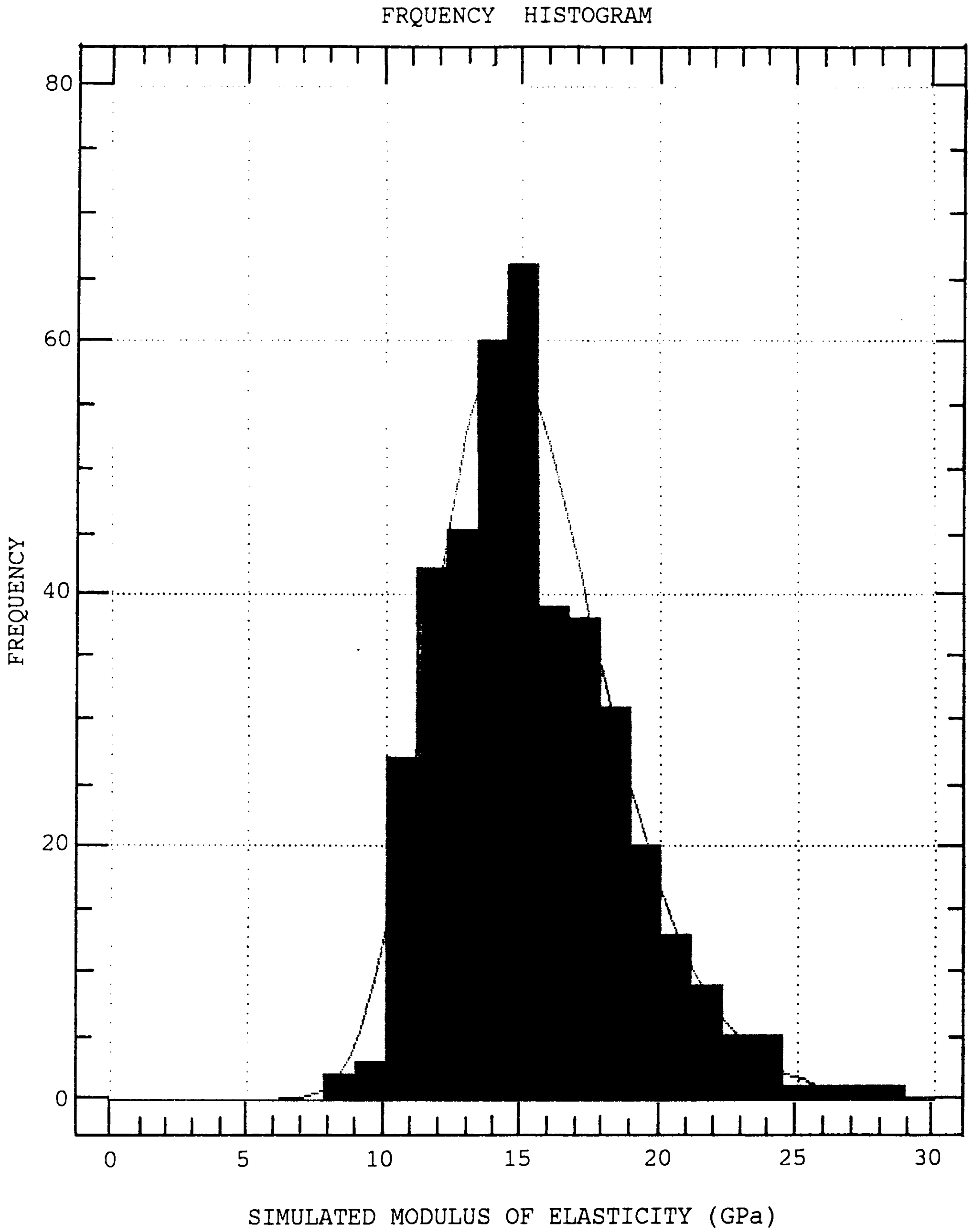

FIGURE 6.7 FREQUENCY HISTOGRAM OF SIMULATED MODULUS OF ELASTICITY.
(MOE, STRENGTH OF TIMBER, STRENGTH OF FINGER JOINTS POSITIVELY CORRELATED)

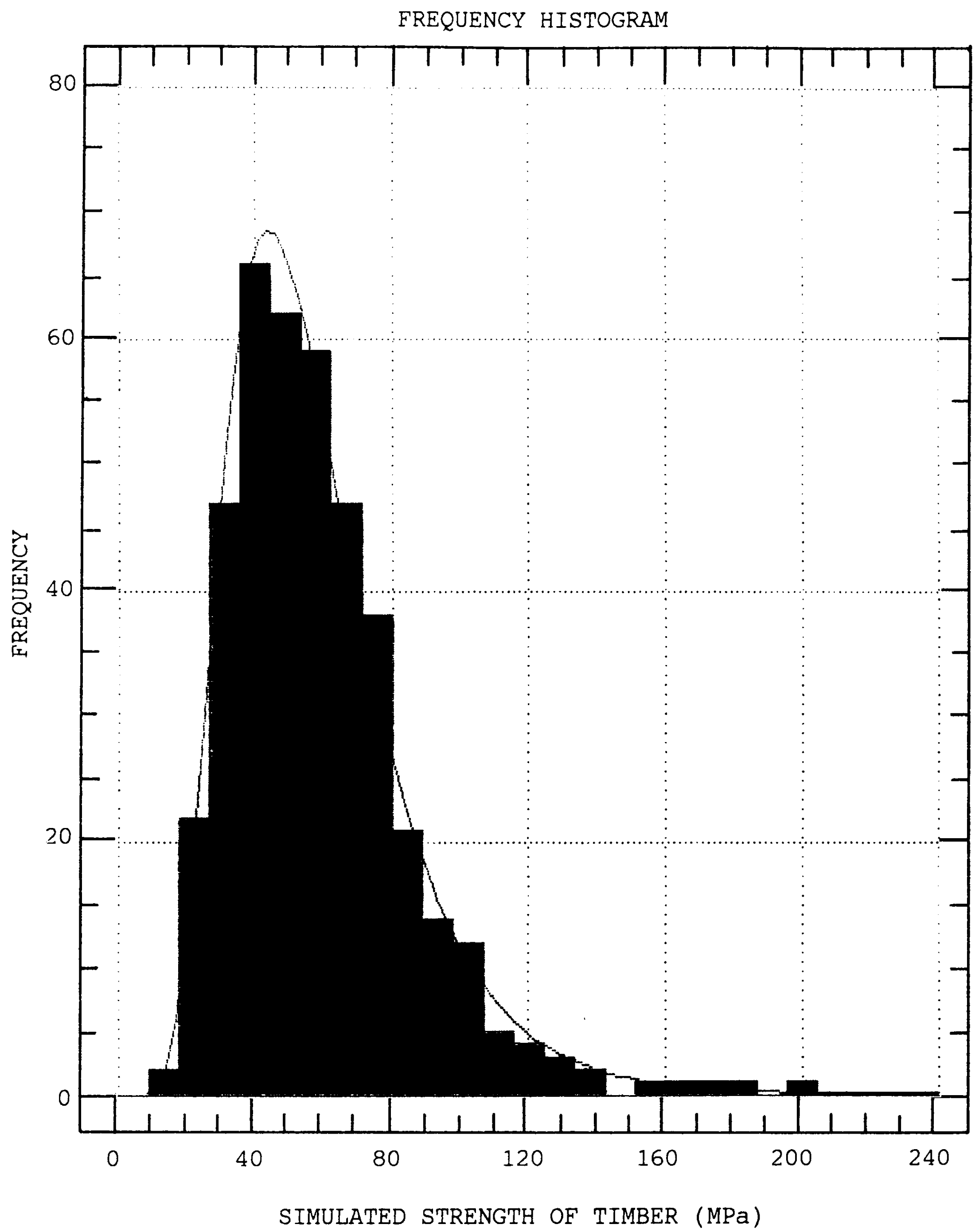

FIGURE 6.8 FREQUENCY HISTOGRAM OF SIMULATED BOARD STRENGTH.
(MOE, STRENGTH OF TIMBER, STRENGTH OF FINGER JOINTS POSITIVELY CORRELATED).

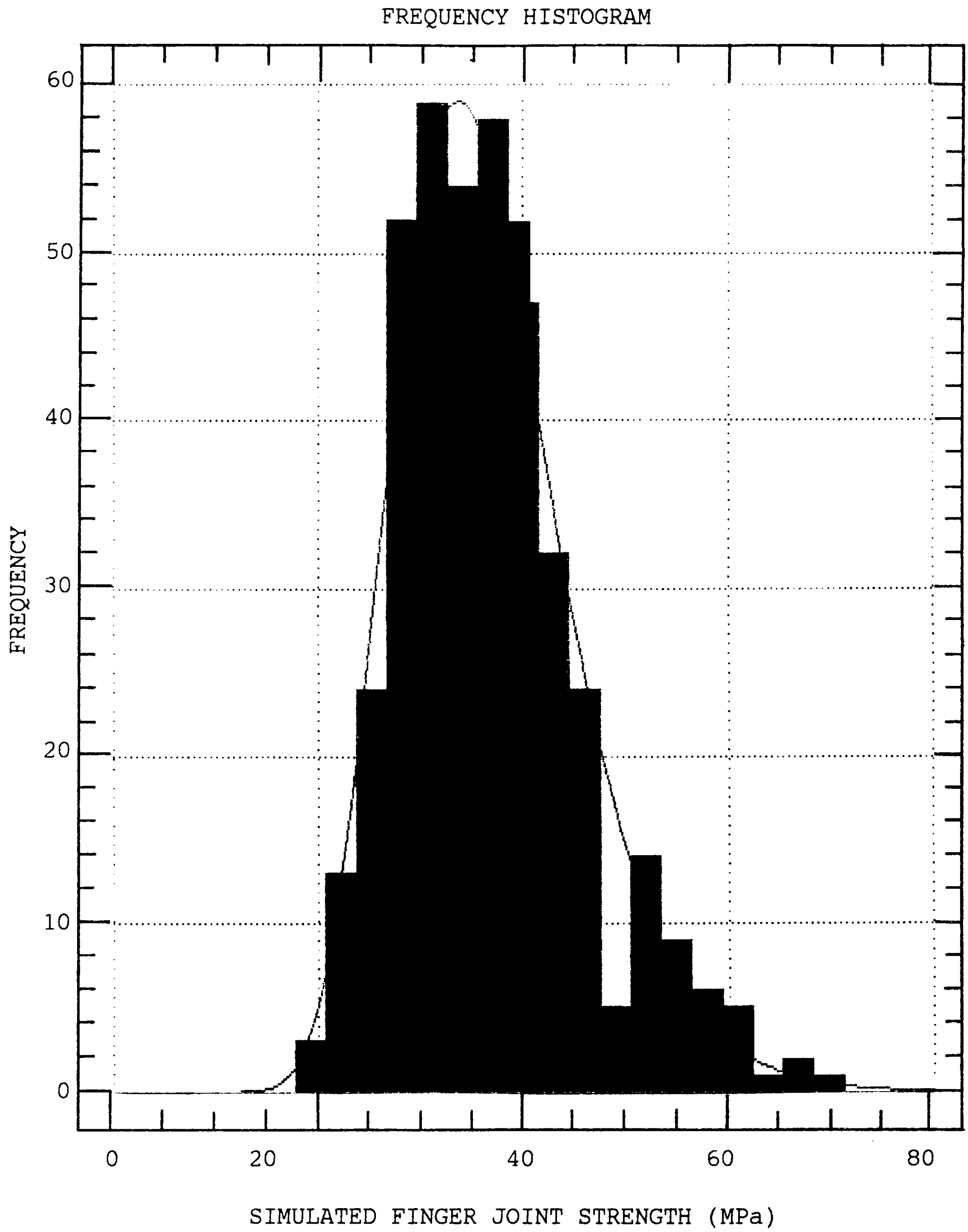

FIGURE 6.9 FREQUENCY HISTOGRAM OF SIMULATED FINGER JOINT STRENGTH.
(MOE, STRENGTH OF TIMBER, STRENGTH OF FINGER JOINTS POSITIVELY CORRELATED).

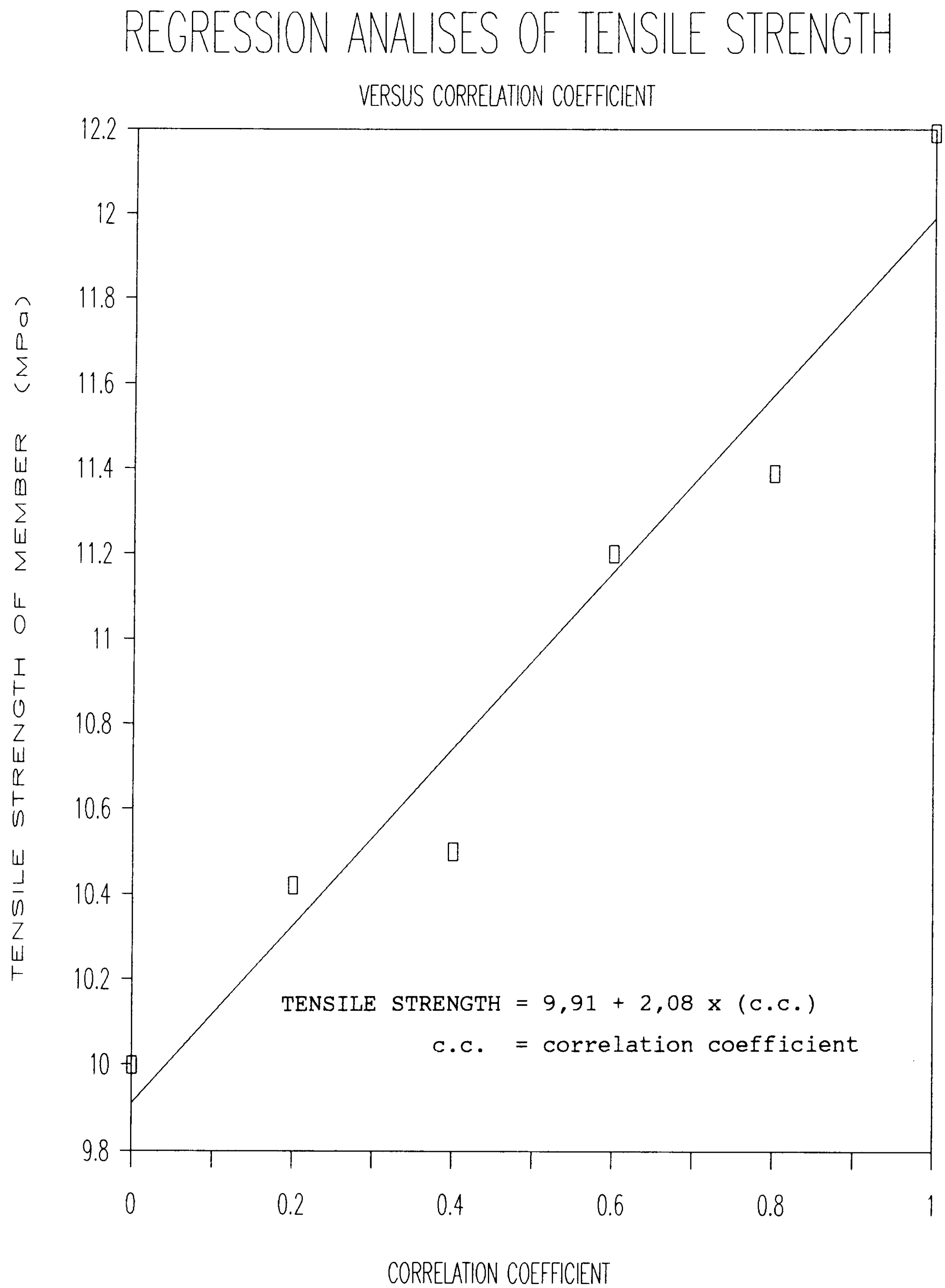

FIGURE 6.10 LINEAR REGRESSION OF TENSILE STRENGTH OF DOUBLE LAMINATED TENSION MEMBERS WITHOUT FINGER JOINTS VERSUS CORRELATION CO-EFFICIENT BETWEEN MODULUS OF ELASTICITY AND STRENGTH OF TIMBER BOARD.

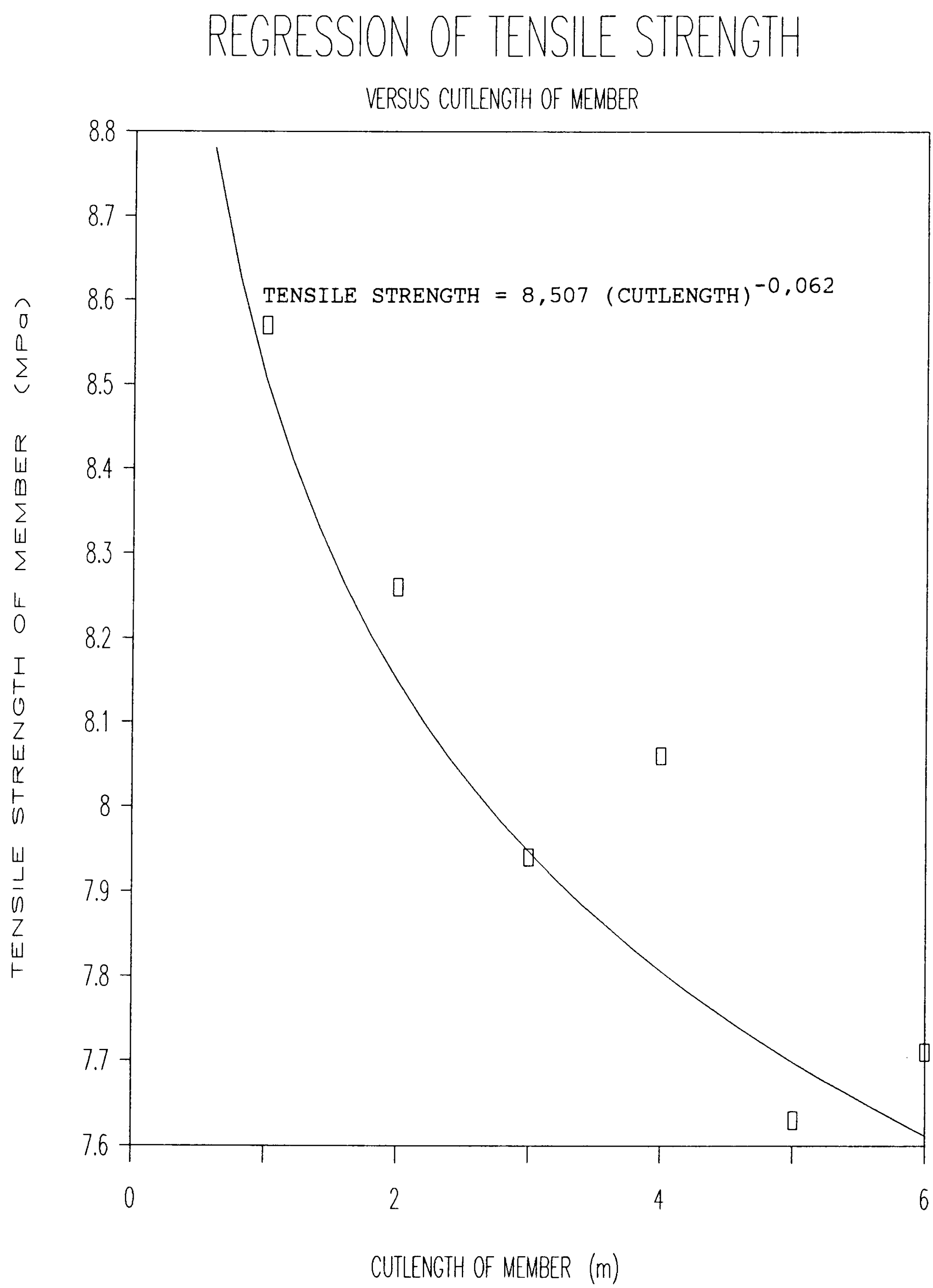

FIGURE 6.11 REGRESSION OF TENSILE STRENGTH OF DOUBLE LAMINATED MEMBER WITH FINGER JOINTS VERSUS CUTLENGTH OF MEMBER MADE UP OF 1 m LONG BOARDS.

7. ESTIMATING THE STRENGTH OF LAMINATED TIMBER FLEXURAL MEMBERS WITH FINGER JOINTS BY USING COMPUTER SIMULATION.

7.1 INTRODUCTION.

The estimation of the strength of laminated *E. grandis* flexural members has always been a problem in South Africa due to the limited money that is spent on timber research and especially on laminated beams as a result of the relatively small volume of timber that is used in this form.

The South African timber design code SABS 0163[7.10] makes no mention of depth effects or any other size effects, such as width and loading. (See references 7.7, 7.9, 7.11, 7.12) Large volumes of timber would be required to examine each of the effects. Bearing in mind that the volume sales of the timber do not warrant such a large experimental programme, a computer simulation method was sought whereby all these effects could be examined and the trends found by this simulation compared to the trends found in published data. If a good correlation could be found between the simulation model and published data the simulation model could be used to predict the strength of South African *E. grandis* flexural members and to suggest factors to allow for the effects mentioned above.

A method is described whereby laminated beams can be simulated so that all the effects mentioned in the above references can be examined. The simulation uses the strength properties of finger joints and the flexural modulus of elasticity. Finger joint strengths can be obtained from a limited number of tests whereas the flexural or even the tensile modulus of elasticity can be obtained from a non-destructive test. The tests that are required for the simulation are thus limited and fairly inexpensive.

7.2 THEORETICAL APPROACHES FOR ESTIMATING BEAM STRENGTH.

7.2.1 THE SIMPLISTIC APPROACH.

Tests that have been done on laminated *E grandis* beams have shown that, in most cases, the beams fail at a finger joint in the tensile zone of the beam. These outer tensile laminates of the beam are assumed to be critical and failure of one of them would cause the beam to fail. If the statistical strength distribution of the finger joints in the timber is known, the beam strength can be determined. The finger joint strength distribution will determine the flexural strength distribution of the beam. The average flexural failure strength of the beam will be equal to the average tensile failure strength of the finger joint. Furthermore, the standard deviation of the flexural failure strength of the beam and the tensile failure strength of the finger joints will be equal.

Using the assumptions above, the predicted mean flexural strength of beams should be 36,4 MPa with a standard deviation of 9,0 MPa. An evaluation of limited tests, done at the University of Pretoria, shows that the assumptions made above lead to unsatisfactory conclusions about the beam strength. (See Table 7.1) The test beams had a mean strength of 25,2 MPa and a standard deviation of 6,4 MPa. This flexural strength is lower than the finger joint strengths would indicate.

Beam No.	Failure stress MPa	Type of Failure
1	15,7	Finger
2	38,8	Timber
3	27,6	Finger
4	22,4	Finger
5	27,3	Finger
6	22,8	Finger
7	19,7	Finger
8	27,0	Timber
9	25,5	Timber
Mean	25,2	
Std Dev	6,4	

Table 7.1: Strength of E grandis test beams

7.2.2 FINITE ELEMENT MODEL.

Foschi and Barrett[7.3] used a finite element approach in simulating the strength of laminated beams. The laminates were divided into 150 mm long cells. Each cell was assigned a strength and a correlated modulus of elasticity. Knots were distributed throughout the laminates on the basis of the observed distribution of knots in the Douglas fir used in their study.

The stiffness of laminates, having cells with knots, was calibrated against tests done by Kunesh and Johnson[7.6] and tests done by McGowan[7.8].

The tensile strength of the timber was modeled using Weibull's theory of brittle fracture and the modulus of elasticity was also assumed to obey a two-parameter Weibull distribution function. Strength and modulus of elasticity were positively correlated. It was assumed that failure could only take place in cells that were subjected to tensile stress.

Non-uniform stress in cells was related to uniform stress by means of a relationship that holds for any level of probability of failure. The failure strength of the beams was calculated using the weakest link theory. A hundred replications of each beam geometry were calculated.

This approach worked well for beams that were constructed of graded material. The finite element method does not seem suitable for use by the laminating industry as it would require something more than a Personal Computer to solve the finite element grid. The method seems more suited to analysis by a main frame computer due to the large number of replications and the size of the finite element grid.

7.2.3 SIMULATION OF STRENGTH WHERE FINGER JOINT FAILURE PREDOMINATES.

7.2.3.1 INTRODUCTION.

A beam is a collection of randomly selected boards each having a given average modulus of elasticity and strength. The modulus of elasticity and the tensile strength of the boards may be positively correlated. The boards are in turn connected in their length by means of finger joints whose strength may be a function of the stiffness or strength of the boards.

Normally or log-normally distributed (Ang and Tang[7.1]) values may be generated using the polar method for normal variants described by Box, Muller and Marsaglia and presented in the book by Knuth[7.5]. These normally or log-normally distributed values can be used to simulate the form of the distribution of the properties of timber, be they strength, modulus of elasticity or dimensions. If the mean and standard deviation of any property, which can be obtained from a limited number of test results, are known, it is possible to simulate the distribution of that property of the timber.

The mechanical properties of a beam laminate can be simulated as follows. Each laminate consists of a number of boards that are joined by means of finger joints. The average stiffness of the board and the strength of the finger joints can be assigned simulated values. The correlation between the strength of the finger joint and the stiffness of the timber can be taken into account using the correlated normal random variable technique (Hart[7.4]). The simulated position of the finger joints can be ascertained along the length of the beam with distances between finger joints either being fixed or having a given statistical distribution. These simulated laminates can then be placed one on top of the other in order to obtain the required depth of beam.

Beam loading is important as various loading configurations are possible. (See Figure 7.1) The loading condition will affect the moment envelope and this in turn will affect the number of finger joints that fall within the area of maximum stress. The probability of a weak finger joint falling in an area of high stress increases with the size of the volume of the high stress. The simulation model will be tested using the four point loading as prescribed by American Society for Testing and Materials[7.2] and the values obtained from the simulations will be compared to values obtained from a limited number of flexural strength tests on beams. Simulation of other loading conditions can be used to determine the effects of the loading patterns.

7.2.3.2 PRELIMINARY METHOD TO TEST SIMULATION THEORY.

The position of finger joints in the outer tension laminates of a beam will determine where failure will be initiated. The stiffness of the beam on either side of a finger joint must be calculated so that the maximum tensile stress at the finger joint can be determined. Failure of the beam will occur when a finger joint in the outer tension laminates reaches failure stress. Failure of a finger joint in the outer laminate will cause directional changes in the stress flow. This will lead to principle tensile stresses with a tensile stress component that is perpendicular to the grain which will cause delamination of that laminate. Foschi et al[7.3] state that defects in inner laminates appear to be stronger than expected due to a "lamination effect". Inner finger joints, that are a form of defect, have also been found to be stronger than expected due to the lateral containment offered by the boards on either side. The inner finger joints should be less likely to fail than the outer finger joints due to this containment. Leicester[7.13] has shown that butt joints in a laminated member are very weak. In Chapter 6 it is shown that the tensile strength of a failed finger joint, which is in effect a butt joint, is so low that crack propagation would in all probability take place.

A preliminary model was used to test the simulation method. This preliminary model would not be applicable to deep beams as it would only take failure of the outer tension laminate into account and made no provision for the apparent strength increase of inner finger joints due to the containment of these.

The preliminary model assumed that the strength of finger joints and modulus of elasticity of the timber are normally distributed and that they showed no positive correlation. Lengths of the boards making up a laminate were assumed to be normally distributed as board lengths used for the test specimens were chosen so that at least one finger joint would fall in the middle third of the bottom laminate. The length of boards in a normal manufacturing process would have random lengths between certain tolerances.

The computer model required the following information:

a) The cut length of the beam;

b) The average length of the boards and the standard deviation;

c) The number of laminates;

d) The average modulus of elasticity of the timber and the standard deviation of the modulus;

e) The average strength of the finger joints and the standard deviation of the strength;

The computer model copies manufacturing procedures in that random board lengths are assumed and that these boards are connected in their length by means of finger joints. When the length of a number of jointed boards becomes greater than the cut length of the beam the first laminate is formed and the remainder of the joined boards, the cut length having been deducted, becomes the first portion of the next laminate.(See Figure 7.2) In this way a beam can be simulated with the position of finger joints being known in the length and depth of the beam. The position of the finger joints is important as a joint is the dividing line between two boards having different moduli of elasticity. Each finger joint is assigned a normalized random strength and each board a modulus of elasticity.

The position of finger joints in the bottom laminate is determined and an equivalent section is calculated at each finger joint using the modular ratio method. The type of loading is taken into account by determining the position of the finger joint relative to the position of maximum bending stress. The finger joint strength is multiplied by a factor so that the the stress at the position of maximum stress is calculated when the finger joint reaches failure stress. The weakest modified finger joint strength then determines the failure strength of the beam. A number of replications are performed to obtain statistically useful values.

7.2.3.3 EXPERIMENTAL RESULTS.

Nine test beams, with dimensions 50x220x4500 mm long were manufactured in the normal process at a laminating factory using *Eucalyptus grandis* boards and finger joints glued with phenol resorcinol formaldehyde. Finger joints were expected to have a mean strength of 36,4 MPa with a standard deviation of 9,0 MPa. (See Figure 7.3) These expected strength values were based on tests done on 300 finger joints at the University of Pretoria by van Rensburg et al[7.14]. The test beams were subjected to the standard four point loading test and developed a mean strength of 25,2 MPa with a standard deviation of 6,4 MPa.

7.2.3.4 RESULTS OF SIMPLISTIC APPROACH.

The simplistic model assumes that the mean flexural strength of the beam is equal to the mean tensile strength of the finger joints and that the coefficient of variation of the strengths would also be equal. Using this method, would lead one to believe that the mean strength of the beam should be 36,4 MPa. This value is too optimistic as it assumes only one finger joint in the critical stress volume and this could lead to dangerous assumptions about permissible flexural stresses for beams.

7.2.3.5 RESULTS OF THE PRELIMINARY SIMULATION MODEL.

The preliminary model was used to generate 100 beams, with a depth of 10 laminates of 22 mm thickness, 4500 mm long with four point loading. The mean modulus of elasticity was taken as being equal to 14,91 GPa with a standard deviation of 3,07 GPa. The modulus of elasticity values were based on 470 tests, the results of which are given in Chapter 2, done at the University of Pretoria. Each specimen took about 3 seconds to generate and test for strength on an OLIVETTI M24 SP personal computer. The mean strength for the simulated specimens was 26,0 MPa with a standard deviation of 5,8 MPa. These values were very encouraging and further simulations of the same beam were undertaken for equal end moment loading, uniform distributed loading and central point loading. The distribution of the strengths for the different loading types are plotted in Figure 7.4 to Figure 7.7. The mean strengths and standard deviations are tabulated in Table 7.2 below.

Type of loading	Mean strength MPa	Std Dev MPa	Permissible MPa
Equal end moments	22,4	6,7	5,1
Four point load	26,0	5,8	7,4
Uniform load	25,7	7,1	6,3
Central point	30,0	10,8	5,5

Table 7.2: Effect of loading on beam strength

7.2.3.6 FURTHER SIMULATIONS.

Further simulations undertaken with the preliminary model were to check the sensitivity of beam strength to the coefficient of variation of the modulus of elasticity and to the length of the individual boards in a laminate. The coefficient of variation of the modulus of elasticity in a 4,5 m beam was taken to be 10%, 20% and 30%, while the variation in the length of the boards, in a 6 m beam, was taken at 1000 mm, 2000 mm and 3000 mm with a coefficient of variation of 10%. A 220 mm deep beam with four point loading was used in all cases. The results of these simulations are given in Table 7.3 and Table 7.4.

Coefficient of variation of E	Mean strength MPa	Std Dev MPa
10%	25,3	7,4
20%	25,3	6,1
30%	25,0	7,6

Table 7.3 : Effect of Coefficient of variation of MOE

Board length mm	Mean strength MPa	Std Dev MPa
1000	21,6	6,2
2000	24,5	6,5
3000	26,8	6,1

Table 7.4 : Effect of board length on the strength of beams

7.2.3.8 DISCUSSION.

The preliminary simulation model, that only uses the outer laminate strength to predict the strength of beams, worked well for shallow beams as the mean strength of the test beams and the mean strength of the simulated beams differed by only 3%. It is important to note that if the mean tensile strength of the finger joints is used as a strength predictor for beams it could lead to unrealistically high strengths being assumed for the beam. The flexural strength of a member should normally be higher than the tensile strength of that member as the volume under maximum stress is less for flexure than for tension. It appears as if this is not true for laminated beams as failure is basically a tensile failure of the weakest laminate in the beam.

Grade stress for timber in Southern Africa is based on the fifth percentile value divided by a factor of safety of 2,22[7.10]. If this is used as a criterion it would lead to a grade strength for the finger joints of 9,7 MPa and a grade strength of 7,4 MPa for the 4,5 m beam tested.

From Table 7.3 it can be seen that the strength of the beam is insensitive to changes in the coefficient of variation of the modulus of elasticity. The length of boards between finger joints, however, has a very large impact on the strength of the beam. If the boards are short the mean strength drops quite dramatically. Using the method for determining the grade stress as given above the 6 m beam with 1000 m boards would have a grade strength of 5,1 MPa. This is very much less than the 9,9 MPa allowed in the present South African Code of Practice[7.10] where no limit is placed on the number of finger joints in a laminate.

7.3 SIMULATION MODEL WITH POSITIVELY CORRELATED MODULUS OF ELASTICITY AND FINGER JOINT STRENGTH.

7.3.1 INTRODUCTION.

The simulation model used in this portion of Chapter 7 differs from the previous model in that the method described in Chapter 6 is used to simulate normally distributed finger joint strengths and moduli of elasticity that are positively correlated.

It is generally agreed (Ozelton[7.9]) that one of the factors that influences the strength of members is the containment of defects. Finger joints that are contained by boards on either side appear to be stronger by between 20% and 30% than uncontained finger joints. Finger joints in inner laminates of laminated beams would have this containment and should appear to be stronger than the finger joints in the outer laminates of laminated beams. The simulation model thus makes provision for this containment of inner finger joints and herein it also differs from the preliminary model. The provision of a containment factor allows the analysis of deeper beams so that finger joints that fall in the bottom quarter of the beam can be analysed for strength.

Another factors that would influence the strength of flexural members is the number of defects in the regions of high stress. This influences can be divided into two separate factors, namely a depth factor and a length factor. The depth factor would be influenced by the number of laminates in a beam while the length factor can be subdivided into two further factors, namely a factor that takes the loading into account and a factor that takes the number of finger joints in a laminate into account.

The model used in all further simulations takes all the above factors mentioned into account. The effect of the variation of the containment factor on the strength of the beams will be looked into. Effects of beam depth, beam length and loading type will also be ascertained.

7.3.2 SIMULATIONS UNDERTAKEN.

7.3.2.1 CONTAINMENT FACTOR.

The strength increase of finger joints in the inner laminates due to the containment factor is assumed to be between 20% and 30%. A simulation was undertaken wherein this containment factor was varied between 0% and 50%, in steps of 10%, in a 15 laminate beam, that is made up of laminates that would have one or two finger joints. Two hundred strength calculations of the beam, that was subjected to four point loading, for each containment factor, were undertaken in which the finger joint strength and modulus of elasticity were varied, using the method described in Chapter 6. The mean strength, standard deviation and permissible stress of each was calculated and a simple regression was performed on the permissible stress versus the containment factor. The plot of the regression is given in Figure 7.8 and the formula for the curve is given by:

$$\text{Permissible stress} = 6,6 \times (\text{Containment Factor})^{0,4838}$$

Permissible stress in MPa.

Further simulations of a 40 laminate beam that was constructed of laminates that had up to six but not less than four finger joints were undertaken to ascertain the effects of the containment factor. Two hundred strength calculations of the beam, for each containment factor, were performed. The mean strength, standard deviation and permissible stress was calculated and a simple regression of permissible stress versus containment factor was performed. The plot of the regression line is given in Figure 7.9 and the formula for the curve is given by:

$$\text{Permissible stress} = 1.16 + 3,33 \times (\text{Containment factor})$$

Permissible stress in MPa.

A much larger scatter of the permissible stress values was found in the case of the deeper beam. However, in both cases the strength increase between a containment factor of 20% and 30% was less than 6%. It was thus decided to use a conservative value of the containment factor of 20% for all further calculations.

7.3.2.2 DEPTH FACTOR.

To ascertain the weakening effect that the depth, i.e. the number of laminates of a beam, has on the strength of the member, simulation of a beam wherein the number of laminates was varied from ten to forty in steps of five was undertaken. The beam was constructed of laminates having one or two finger joints and was subjected to four point loading. Two hundred replications of each beam layout were simulated and the strength determined. The mean strength, standard deviation and permissible stress for each beam layup were calculated and a simple regression of permissible stress versus number of laminates was undertaken. The results of the regression are given in Figure 7.10 and the formula for the curve is given by:

$$\text{Permissible stress} = 11,08 \times (\text{No of laminates})^{-0,1596}$$

Permissible stress in MPa

This shows that there is a depth factor for beams that are made up of similar laminates. The permissible stress of a ten laminate beam would be about 25% greater than that of a forty laminate beam.

7.3.2.3 LENGTH FACTOR i.e. NUMBER OF FINGER JOINTS.

To ascertain whether a length factor exists for laminated beams a 10 m, 20 laminate beam was simulated. The length of the boards that make up the laminates was varied from 1 m to 5 m in steps of 1 m with a coefficient of variation of 20%. Four point loading was applied to the beam and the strength, standard deviation of the strength and the permissible stress was calculated. A simple regression of permissible stress versus board length was performed and the results are given in Figure 7.11. The formula for the curve is given by:

$$\text{Permissible stress} = 4{,}315 + 0{,}587 \times (\text{Mean board length in m})$$

Permissible stress in MPa.

The results of this simulation confirm the results that were obtained in Chapter 6 in that the greater the number of finger joints that appear in a laminate the smaller the permissible tensile stress of that laminate becomes. The physical number of finger joints in the tension laminates and especially in the outer laminate, determines the strength of laminated *E. grandis* beams. This differs somewhat from the traditional concept of length effect in that short beams with many finger joints in the tension laminates can be weaker than long beams with fewer finger joints in the tension laminates.

In order to compare this simulation method with test results obtained by Madsen[7.7] further simulation for length effect were undertaken. The length of the individual boards of a 10 laminate member was kept constant at 1 m with a coefficient of variation of 20% and the length of the beam varied from 2 m to 8 m in steps of 1 m. A simple regression was undertaken and the results are plotted in Figure 7.12. The equation of the regression line is given by:

$$\text{Permissible stress} = 8{,}56 \times (\text{Length in m})^{-0{,}1677}$$

Permissible stress in MPa.

7.3.2.4 FACTOR FOR TYPE OF LOADING.

The modified brittle fracture theory would predict that a flexural member that is subjected to equal end moments would show a lower strength than a flexural member that is subjected to a point load as the volume of timber under maximum stress is greater for equal end moments than for the point loading. To ascertain the effects of the loading type a simulation of a 6 m, 15 laminate beam, where the laminates were made up of boards that had an average length of 2 m, was undertaken. The four basic loading patterns as given in Figure 7.1 were applied, two hundred replications of each loading pattern were undertaken and the mean strength, standard deviation of the strength and the permissible stresses were determined. The results of the simulation are given in the Table 7.5 below

Type of loading	Mean strength MPa	Std Dev MPa	Permissible MPa
Equal end moments	20,62	5,85	4,94
Four point load	24,27	5,51	6,84
Uniform load	24,80	6,28	6,51
Central point	29,64	6,47	8,54

Table 7.5: Effect of loading on strength of beam

The simulation of the load type shows a very strong loading effect. This loading effect would be less noticeable if longer boards that make up the laminates were used as this would lead to less finger joints in the tensile zone. The simplified method, given in paragraph 7.1.3.5, does not show this effect as well as the method that uses the correlation between finger joint strength and modulus of elasticity. The task of defining a loading effect factor is complicated by the length factor, i.e. number of finger joints in the laminates. Most beams are subjected to uniform loading which compares very favourably with the four point loading. In the rare cases where beams may be subjected to the more critical equal end moment loading, permissible stresses should be reduced.

7.4 COMPARISON WITH OTHER THEORETICAL METHODS.

The depth effect will be compared with the modification factor of CP 112:Part 2:1971 for laminated beams as well as with the modification factor that can be calculated using the modified brittle fracture theory of Madsen and Buchanan[7.7]. The length and loading effect will be compared to the length and loading effect found by Madsen and Buchanan[7.7].

7.4.1 DEPTH EFFECT COMPARISON.

The depth effect described by CP 112:Part 2:1971 and BS 4978:1973 for beams with a depth greater than 300 mm is given by:

$$K_{16} = 0,81 \times \frac{(D^2 + 92\ 300)}{(D^2 + 56\ 800)}$$

where D is the depth in mm.

The modified brittle fracture theory states that :

$$\frac{X_1}{X_2} = \left[\frac{d_2}{d_1}\right]^{1/k_2}$$

where: X_1 and X_2 are the failure stresses
d_1 and d_2 the corresponding depths of the members
k_2 a factor that depends on the variability of the material.

Values for k_2 can be calculated from the two parameter Weibull distribution. If the coefficient of variation for the two parameter Weibull distribution is known and $X_0 = 0$ (minimum value is zero) a simplified approximation for k_2 is given by Madsen and Buchanan.

$$\text{Coefficient of variation} = k_2^{-0,922}$$

If the coefficient of variation for the finger joints is 0,247 then a value of 4,55 for k_2 is obtained.

A tabulated comparison of the simulation method, CP 112 modification factor and the method of Madsen is given below. The depth effect in all cases is compared to a standard depth of 300 mm which is given a modification factor of unity.

Depth of beam mm	Simulation	CP 112	Madsen method
300	1,000	1,000	1,000
440	0,941	0,925	0,919
660	0,882	0,868	0,841
880	0,842	0,845	0,789
1320	0,790	0,826	0,722

Table 7.6: Comparison of depth effects

Moody *et al*[7.11] found that when their test data was used to calibrate the following size effect formula used by the ASTM D 07.02.02 task committee, a value of 10 for the exponent *x* resulted.

$$R = R_0 K \left[\frac{d_0}{d}\right]^{1/x} \left[\frac{l_0}{l}\right]^{1/y} \left[\frac{w_0}{w}\right]^{1/z}$$

Where: R is the strength of the beam with dimensions d, l, w;
R_0 is the strength of the standard beam of dimensions d_0, l_0, w_0;
K is the factor that indicates the type of loading;
d_0, l_0, w_0 are the dimensions of the standard beam;
d, l, w are the dimensions of the beam under consideration;
x, y, z are the exponents that were to be determined.

The simulation model predicts a value of 6,3 for the exponent *x* whereas the method used by Madsen et al[7.7] would predict a value of 4,55. It appears that the variability in the strength of the material used for the data of Moody et al[7.11] was less than the variability in strength of the material used in this study. The depth effects compare very favourably and it should be noted that the formula given by CP 112 could be used to predict the strength of deep *E grandis* beams. As the South African timber design code SABS 0163[7.10] makes no provision for a depth effect, this is seen as a topic that requires urgent attention.

7.4.2 LOADING EFFECT.

The loading effect is tabulated in the publication by Madsen and Buchanan[7.7] and if the four point loading is taken as the standard with a modification factor of unity the values of the simulation and the Madsen values can be compared in the following Table 7.7.

Loading type	Simulation	Madsen
Equal end moments	0,72	0,81
Four point loading	1,00	1,00
Central point load	1,25	1,25

Table 7.7: Comparison of loading effect

The loading effect obtained from the simulation of beams compares favourably with the values obtained by Madsen *et al*. Fortunately, very few beams are subjected to more stringent loading conditions than a uniform loading condition so that the loading effect should not present any problems. Beams that are subjected to point loading could benefit from the loading effect and could have permissible stresses that are 25% higher than for beams with a uniform loading.

7.4.3 LENGTH EFFECT.

The length effect as described by Madsen *et al*[7.7] is tabulated in the publication and a direct comparison can be made. Four point loading on a 3 m span is taken as the standard with a modification factor of unity. The comparison is given in Table 7.8 below.

Length of beam mm	Simulation	Madsen
1000	1,20	1,37
2000	1,07	1,12
3000	1,00	1,00
4000	0,95	0,92
5000	0,92	0,86
6000	0,89	0,82
7000	0,87	0,79

Table 7.8: Comparison of length effects

The length effects differ significantly. Moody *et al* found that a value of 10 for the exponent *y* in the ASTM formula gave the best fit whereas the values given by Madsen *et al* would result in a value of 3,5 and the simulation a value of 6. The timber tested by Madsen *et al* must have had a much higher variability in strength than that tested by Moody *et al*. The number of finger joints in the tension laminates of laminated beams is critical. The simulation method has an advantage over the values given by Madsen and Moody as it gives the manufacturer a method of calculating the strength of his laminated beams when the strength of the finger joints and the distance between the finger joints is varied.

7.5 CONCLUSION.

Beam strengths obtained from the simulation method, that uses the correlation between finger joint strength and modulus of elasticity, compare very favourably with the laboratory test results. The method is comparatively simple to use and could give the manufacturer an estimated strength for the beams. This estimated strength could be used as a benchmark for proof loading of the beams and would allow center point loading to be used, as the simulation allows a comparison between four point loading and center point loading.

This simulation method shows that a depth factor exists, that this factor is significant and should be taken into account when designing deep beams. The good correlation between the values of the depth factor obtained by the simulation and the depth factor given in CP 112[7.12], shows that assumptions made about the containment factor are in the right order of magnitude. The reduction factor for depth as given in CP 112 should be incorporated in the South African timber design code SABS 0163[7.10].

The length and loading factors cannot be separated as they are very dependent on the number of finger joints in the laminates. A basic permissible stress should be defined and this stress reduced according to the average number of finger joints in the tensile laminates. The reduction formula given in Chapter 6 paragraph 6.5.2 could serve as a basis for such a formula. If the manufacturer of laminated timber has computing facilities, he could use the simulation method to determine permissible stresses for beams of any length and with any number of finger joints.

Although the conclusion, that the simulation method works well, is based on a comparison between a limited number of test results and simulated results, enough variables are built into the simulation model to allow this model to be calibrated, if necessary. However, it is felt that the results obtained from the depth factor simulation and the loading pattern simulation agree so well with results obtained by Madsen *et al*[7.7], that it is safe to assume that the simulation method can be used by manufacturers of laminated *E. grandis* beams to determine permissible stresses. The permissible stresses obtained by using the simulation methods will be far more reliable than permissible stresses that are obtained by blindly applying stress reduction factors. Stress reduction factors should be written in timber codes so that designers can calculate preliminary sizes. The manufacturers of laminated beams should, however, have the computing facilities to calculate various optional layups so as to construct the most economical beam.

7.6 REFERENCES:

7.1 ANG, A.H.S., and TANG, W.H., 1975. Probability Concepts in Engineering Planning and Design. Volume 1 - Basic Principles. John Wiley and Sons, New York. 405 pp.

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7.13 LEICESTER, R.H., 1985, "Glued Laminated Timber." Notes from a Course on Timber Engineering. University of Pretoria, Pretoria, South Africa.

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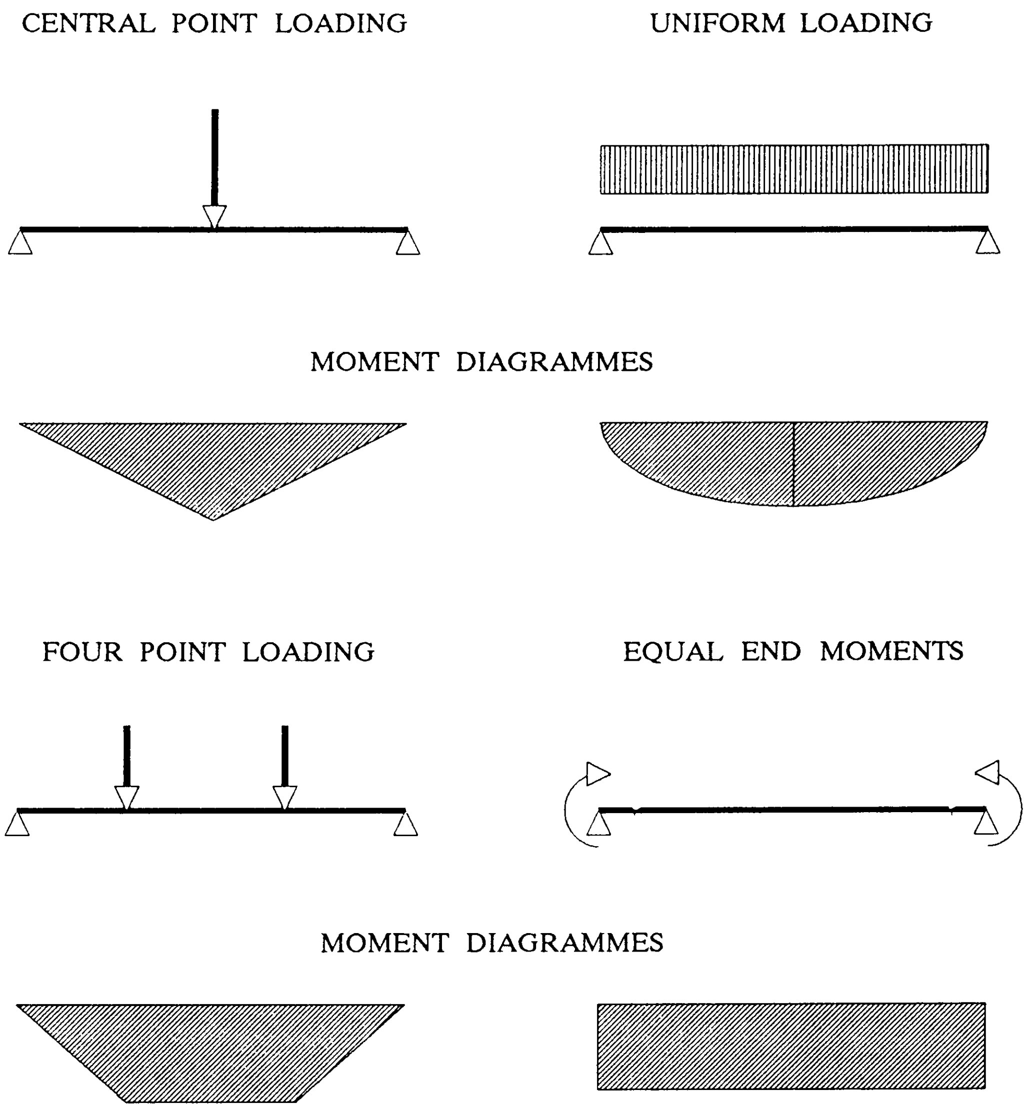

FIGURE 7.1: TYPES OF LOADING.

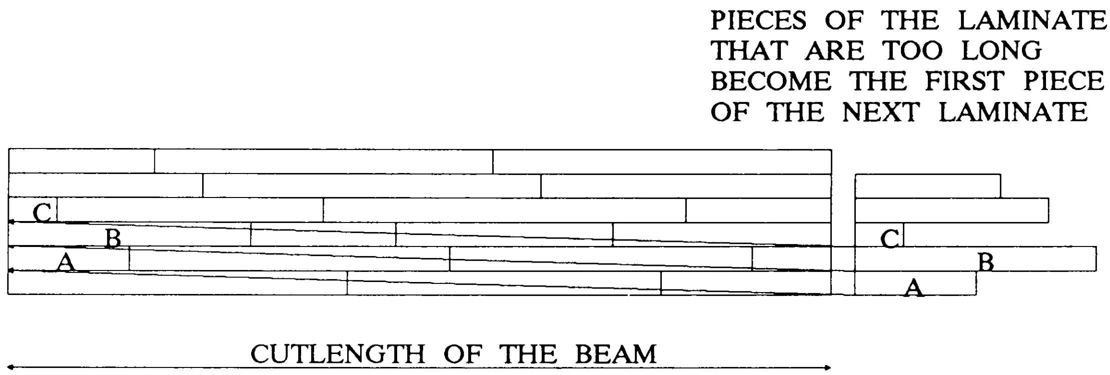

FIGURE 7.2: POSITIONING OF THE FINGER JOINTS.

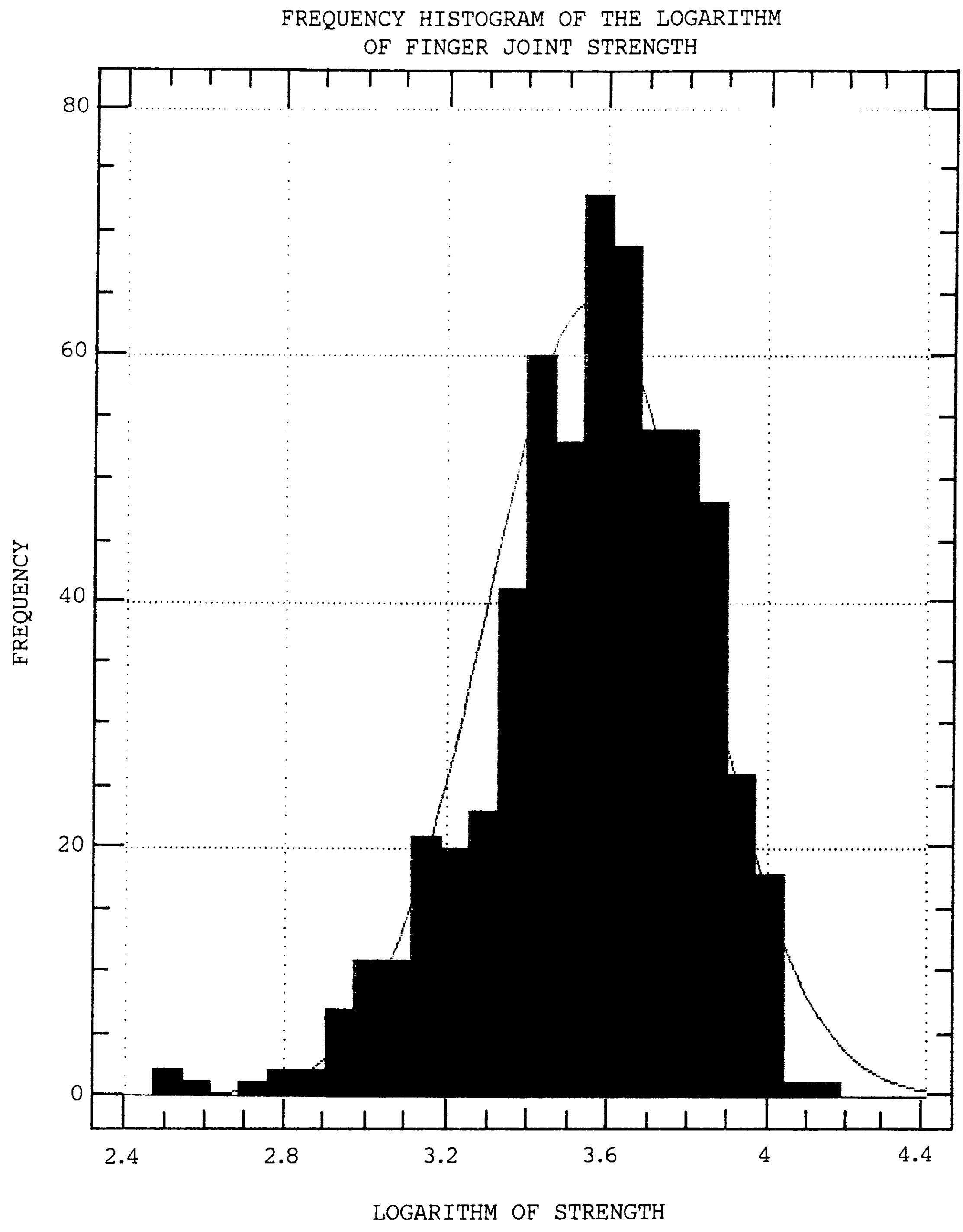

FIGURE 7.3 FREQUENCY DISTRIBUTION OF THE NATURAL LOGARITHM OF FINGER JOINT STRENGTHS OF FINGERS GLUED WITH PHENOL RESORCINOL FORMALDEHYDE.

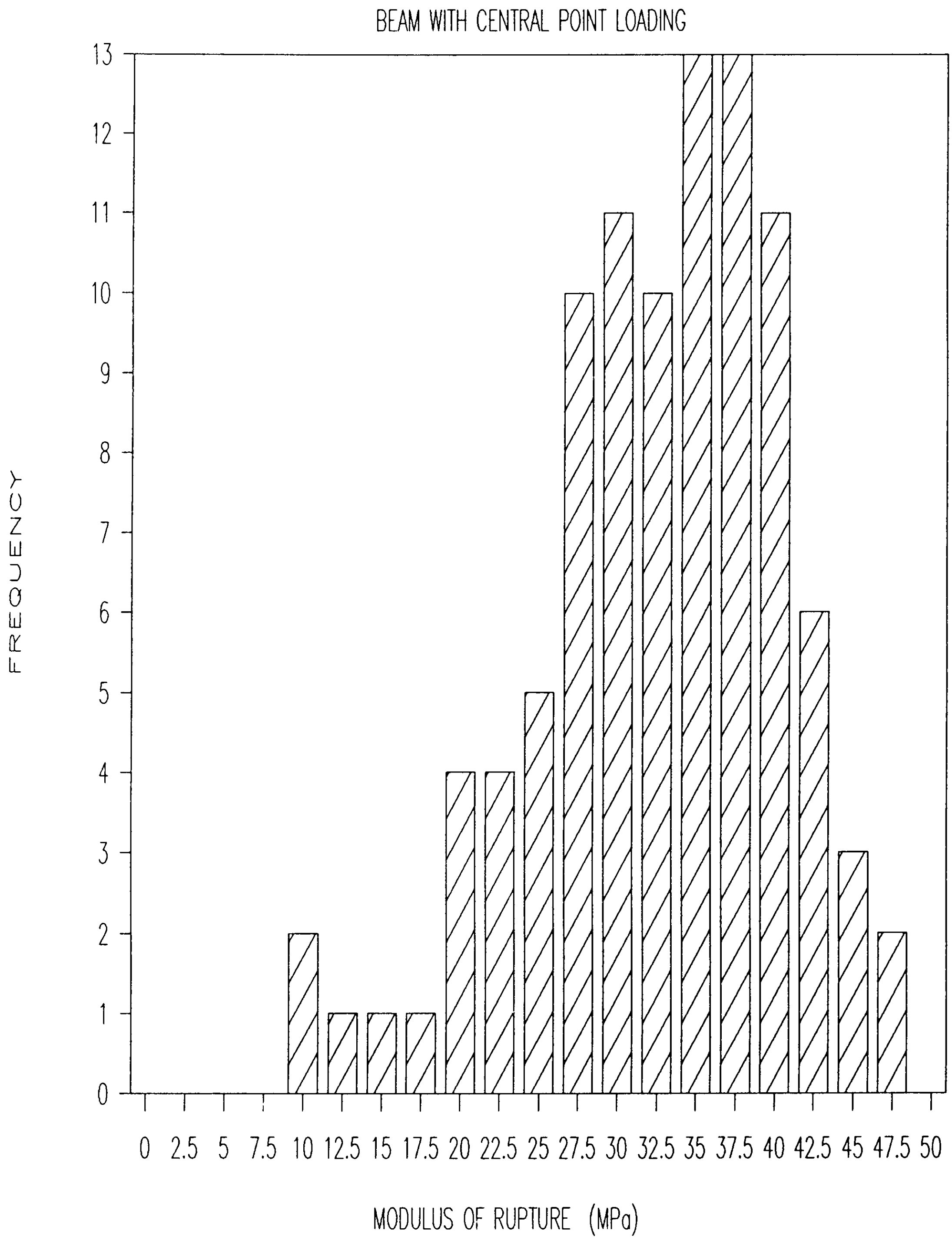

FIGURE 7.4 FREQUENCY DISTRIBUTION OF MODULUS OF RUPTURE FOR BEAM WITH CENTRAL POINT LOAD.

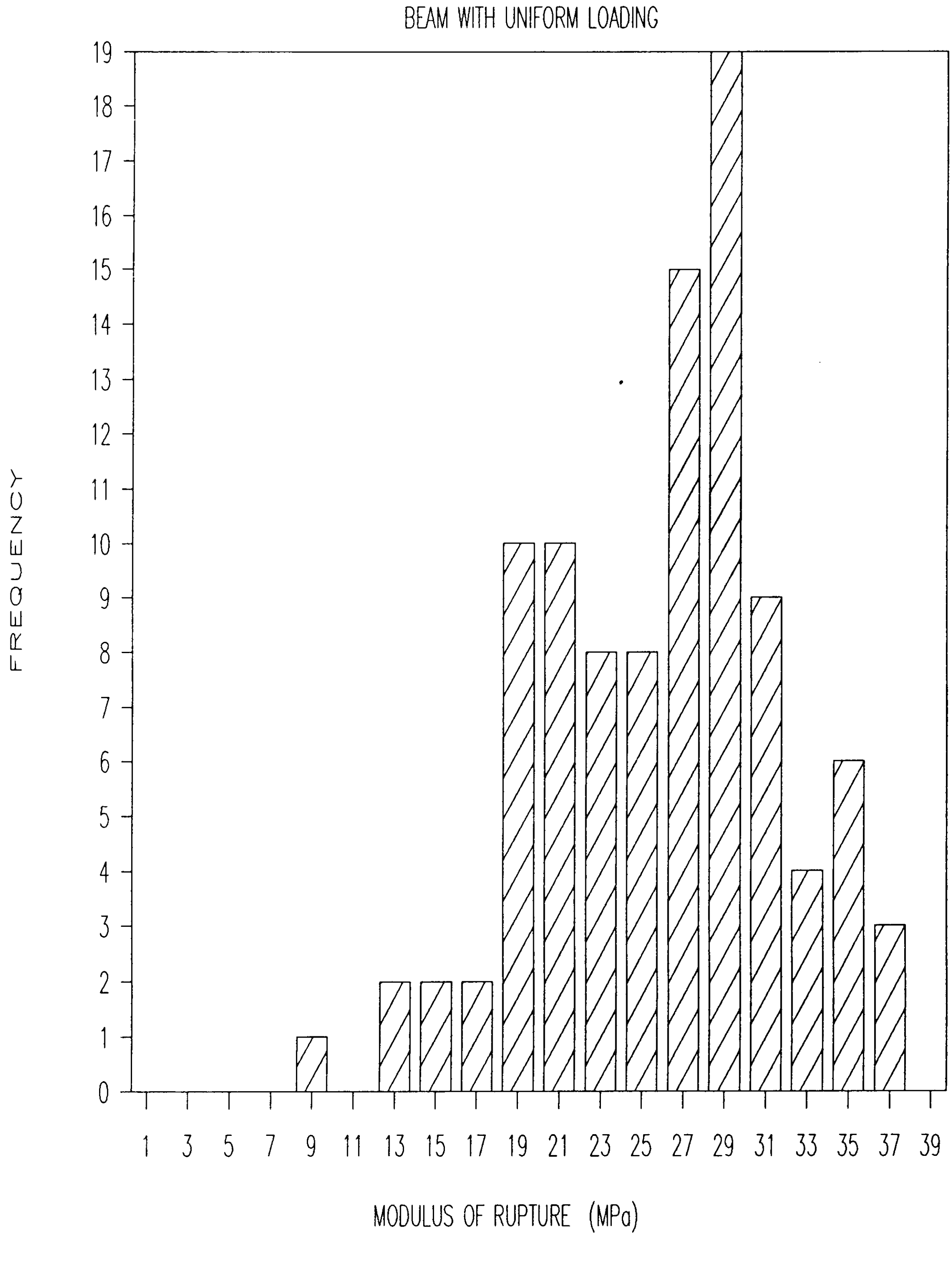

FIGURE 7.5 FREQUENCY DISTRIBUTION OF MODULUS OF RUPTURE FOR BEAM WITH UNIFORMLY DISTRIBUTED LOADING.

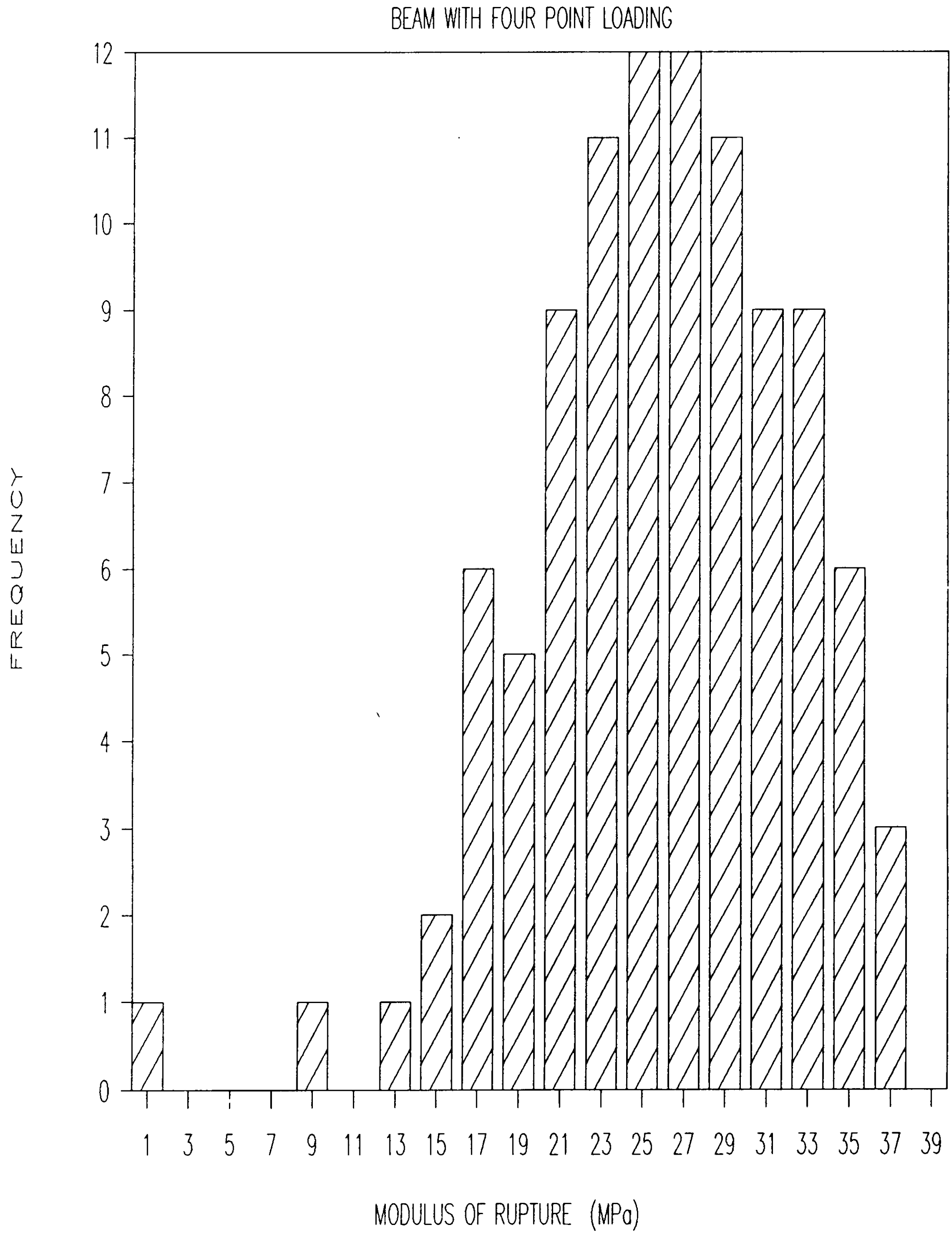

FIGURE 7.6 FREQUENCY DISTRIBUTION OF MODULUS OF RUPTURE FOR BEAM WITH FOUR POINT LOADING.

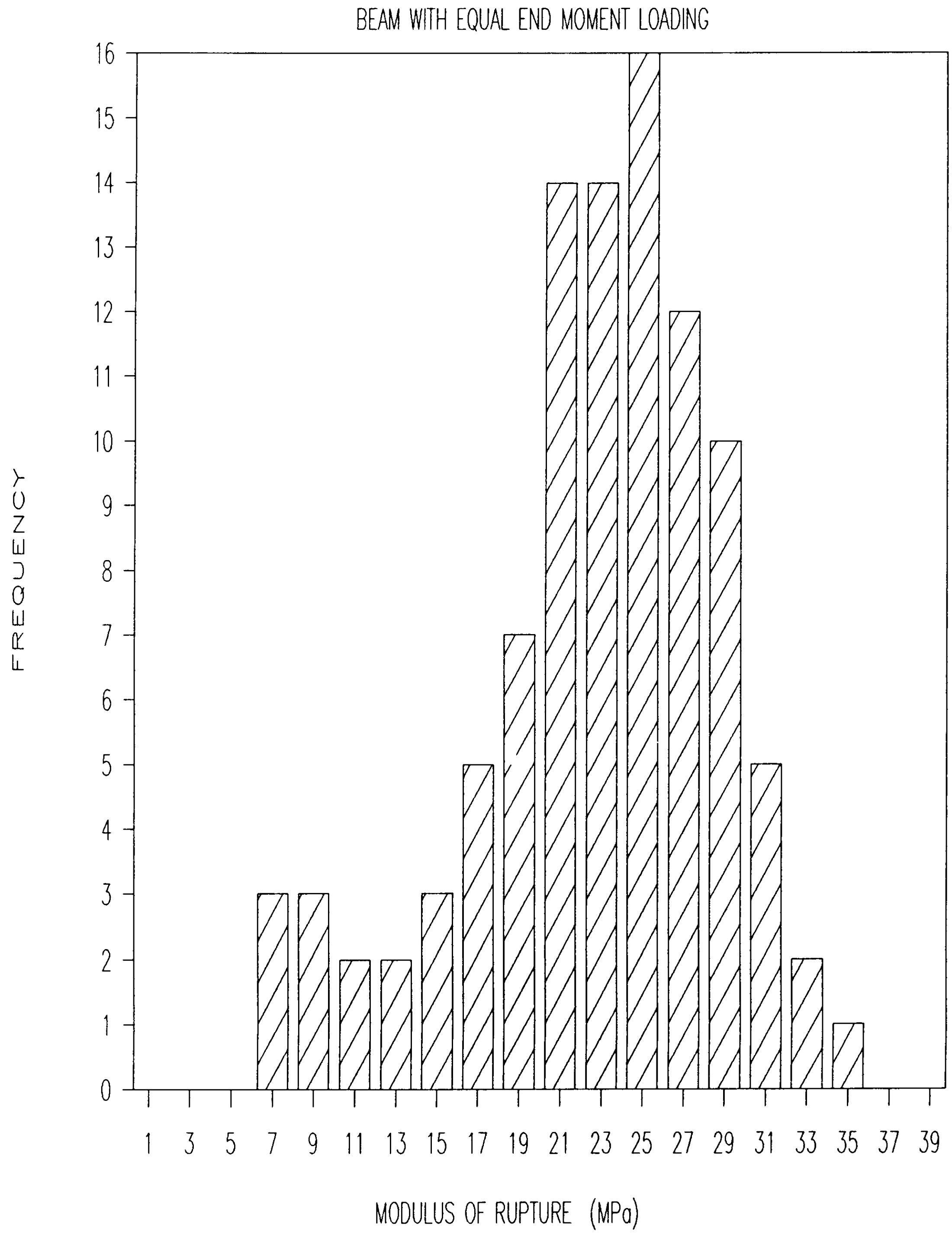

FIGURE 7.7 FREQUENCY DISTRIBUTION OF MODULUS OF RUPTURE FOR BEAM WITH EQUAL END MOMENTS.

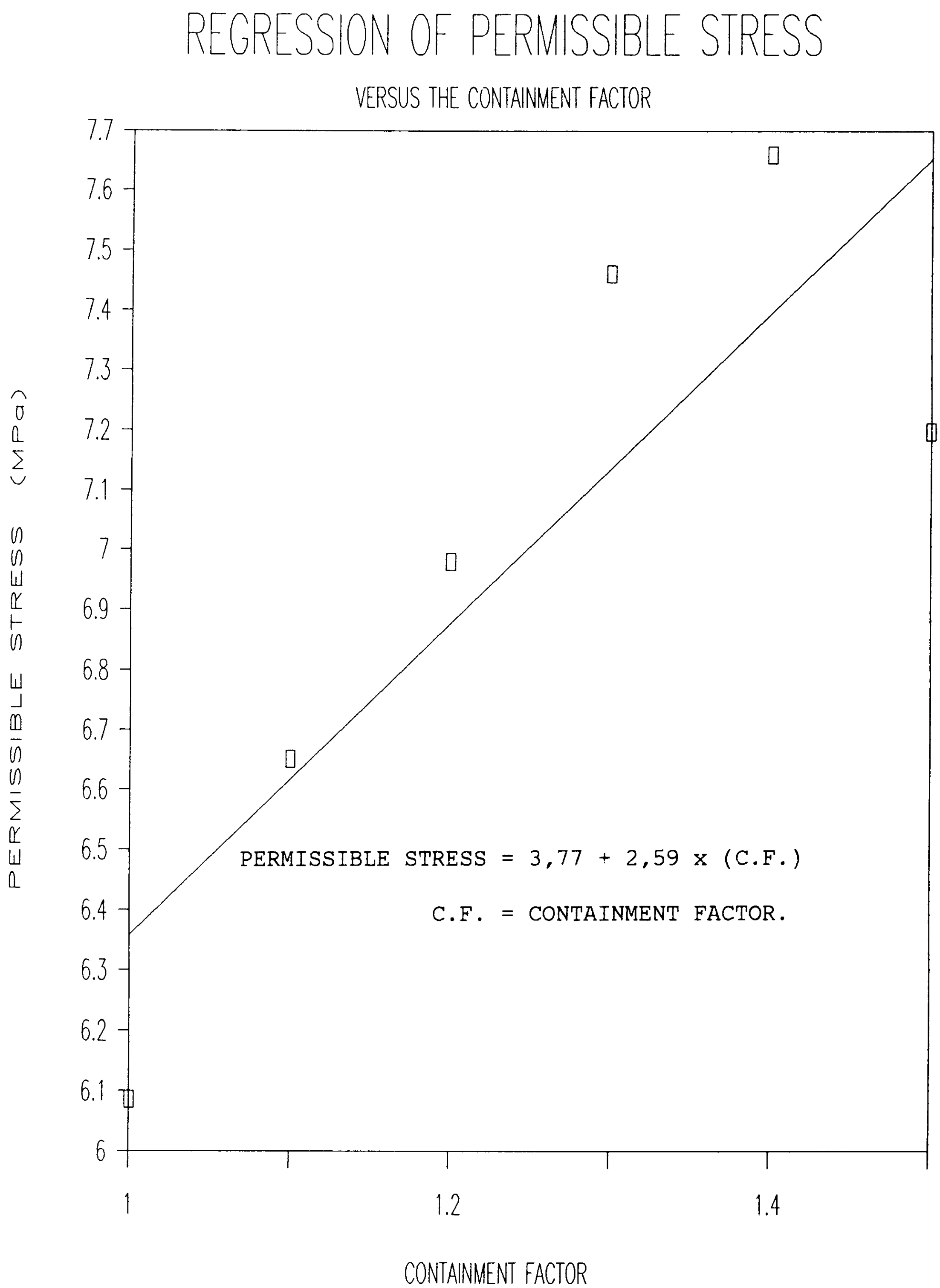

FIGURE 7.8 REGRESSION OF PERMISSIBLE STRESS VERSUS CONTAINMENT FACTOR FOR A 15 LAMINATE BEAM, LENGTH OF INDIVIDUAL BOARDS KEPT CONSTANT.

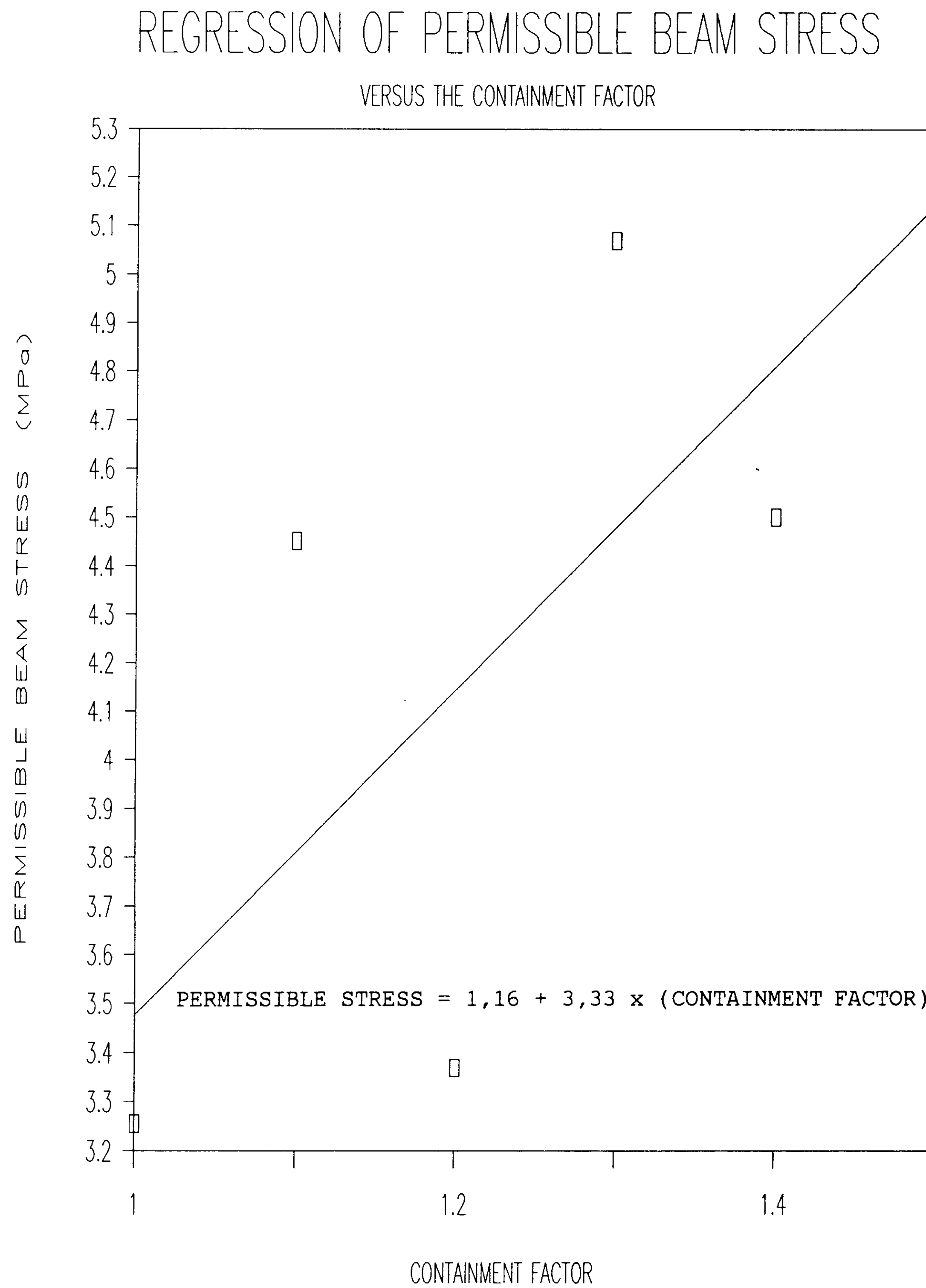

FIGURE 7.9 REGRESSION OF PERMISSIBLE STRESS VERSUS CONTAINMENT FACTOR FOR A 40 LAMINATE BEAM, LENGTH OF INDIVIDUAL BOARDS KEPT CONSTANT.

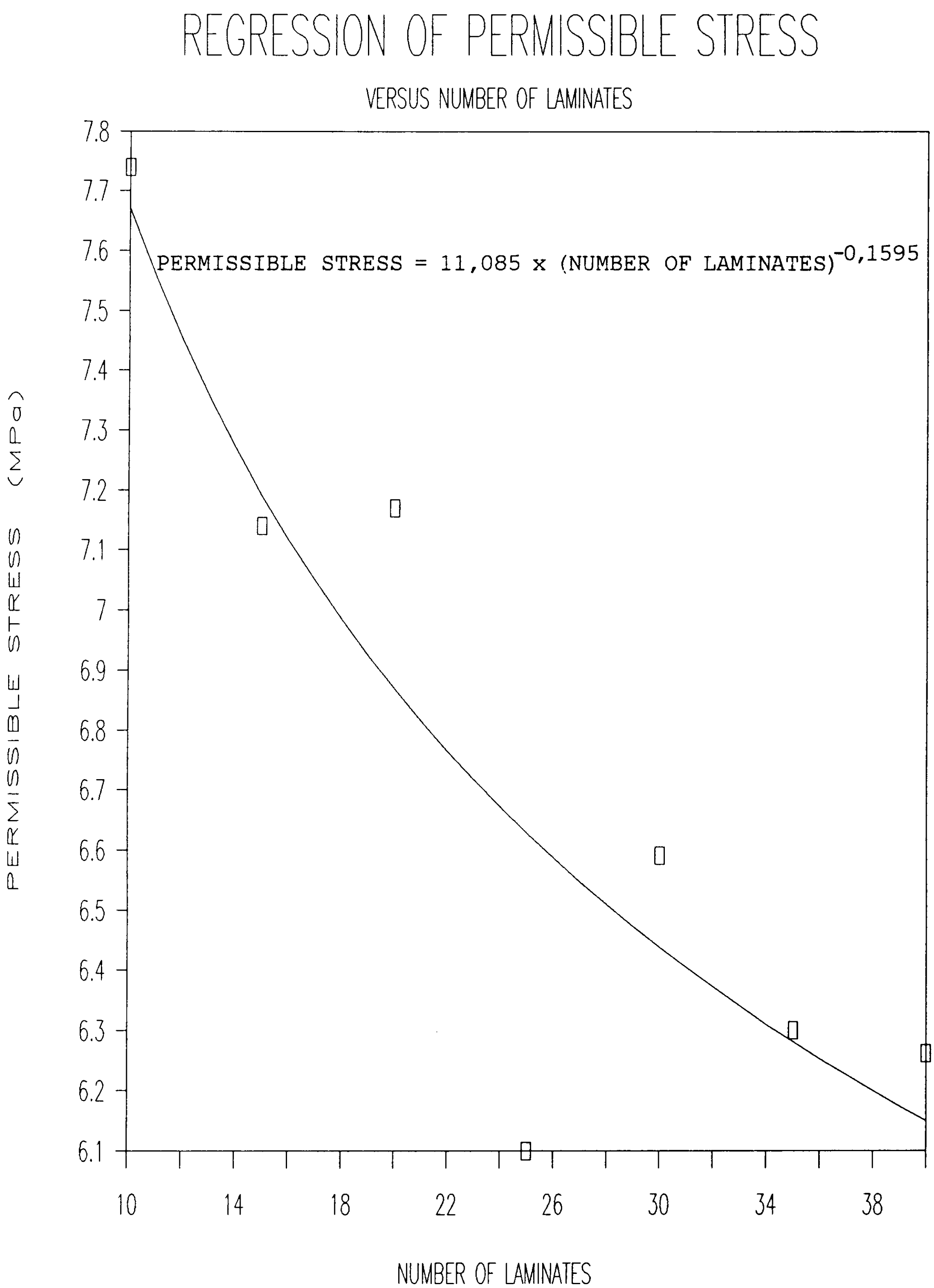

FIGURE 7.10 REGRESSION OF PREMISSIBLE STRESS VERSUS THE NUMBER OF LAMINATES OF A BEAM, LENGTH OF INDIVIDUAL BOARDS KEPT CONSTANT.

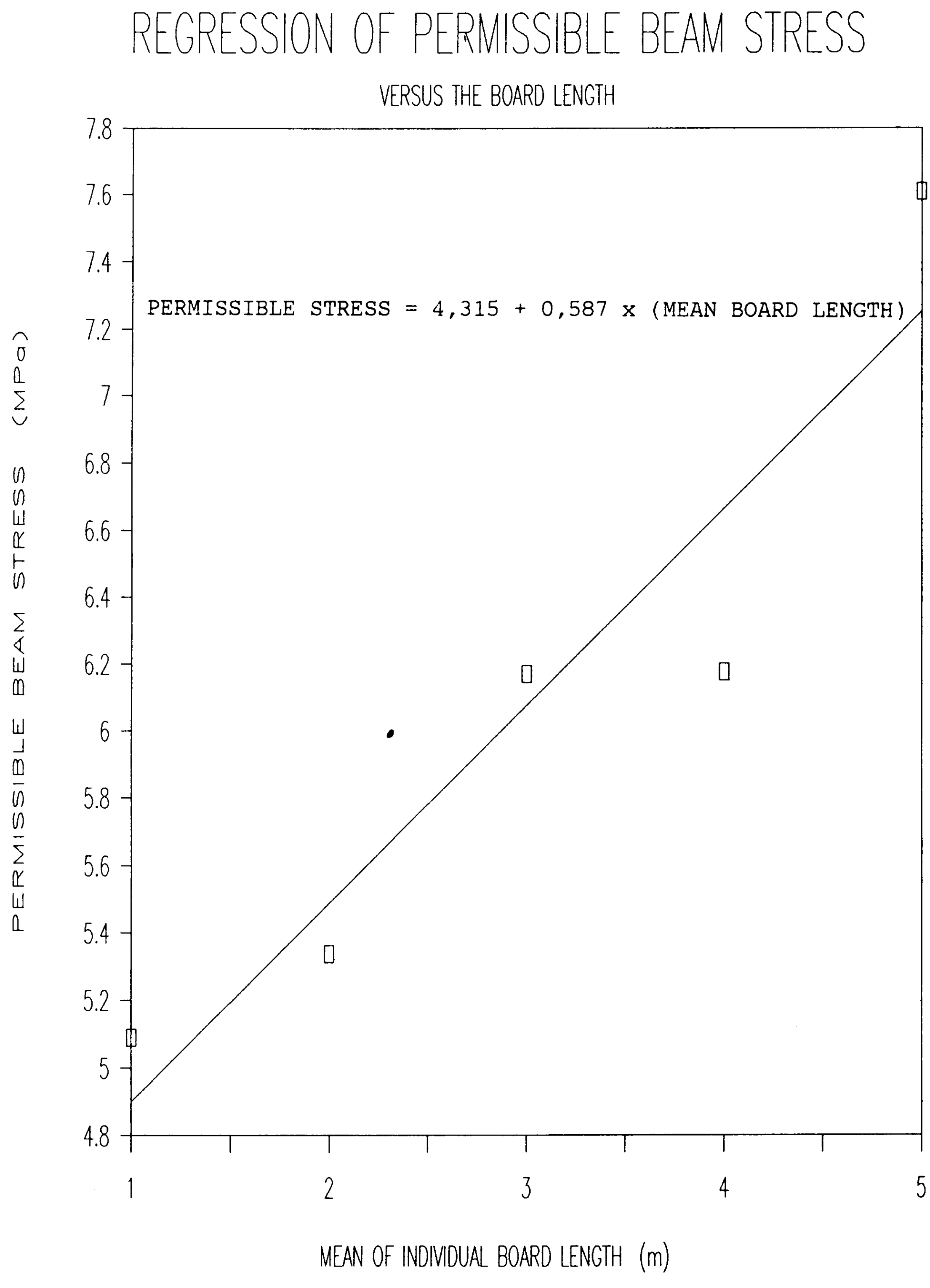

FIGURE 7.11 REGRESSION OF PERMISSIBLE STRESS VERSUS MEAN LENGTH OF BOARD FOR 10 m LONG, 20 LAMINATE BEAM.

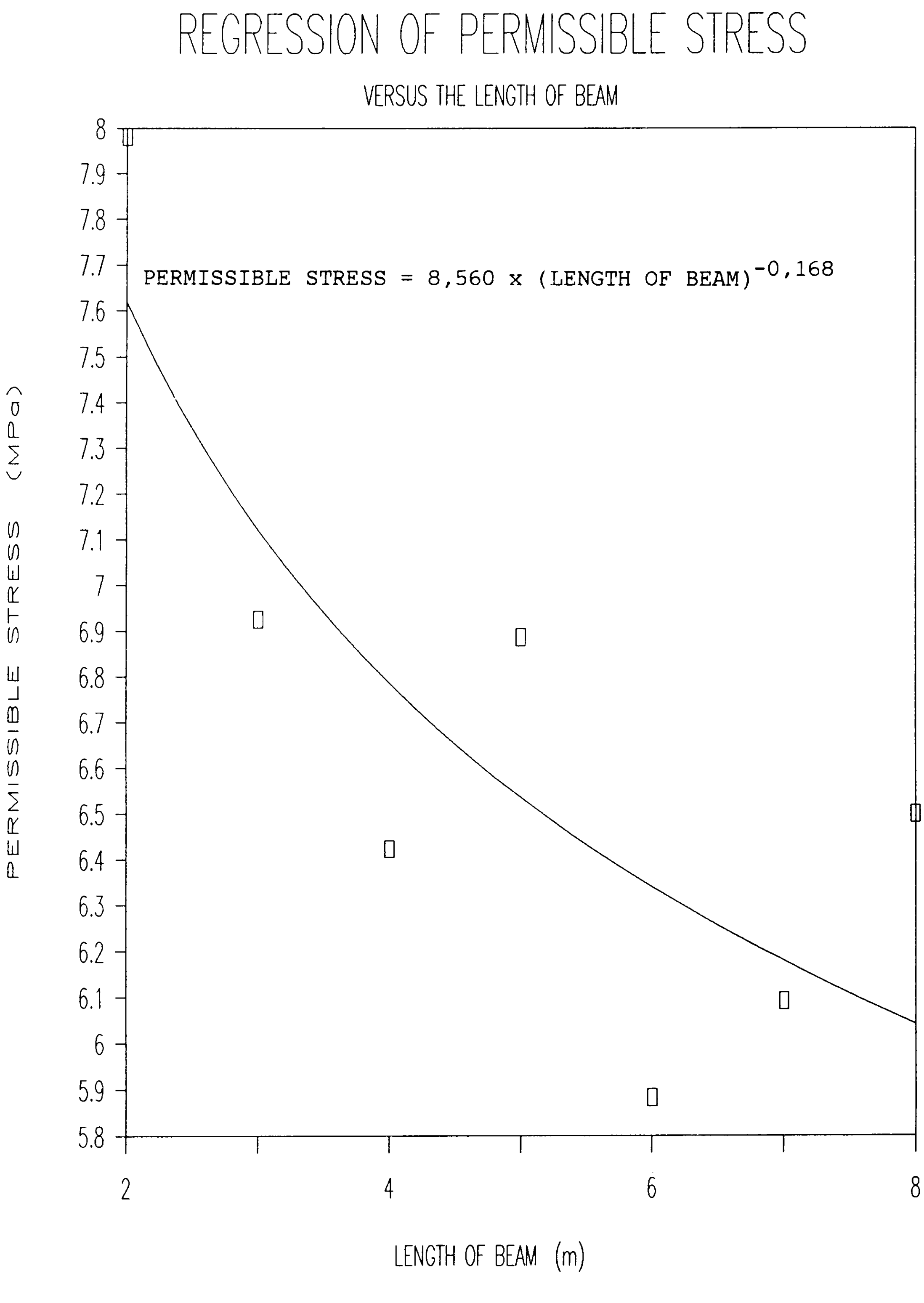

FIGURE 7.12 REGRESSION OF PERMISSIBLE STRESS VERSUS THE LENGTH OF BEAM, LENGTH OF INDIVIDUAL BOARDS KEPT CONSTANT, FOR A 10 LAMINATE BEAM.

8. CONCLUSION.

8.1. LIMITATIONS AND ASSUMPTIONS OF THE SIMULATION MODEL.

The simulation method that is described in this study is based on results of tests carried out on a sample from a population of timber boards from the Politsi area of the Northern Transvaal in South Africa. These boards were tested for the various properties that were required for the simulation model. Tests, for shear strength and tensile strength vertical to the grain, were also required to determine whether laminates with failed finger joints had sufficient residual strength so that they had to be taken into account in the simulation model. The values obtained from the simulations would only pertain to the timber from the population that was tested and should not be applied to all *E grandis*.

The strength distribution of finger joints was based on the test results of approximately 400 finger joints, in timber from the Politsi area in the Northern Transvaal, that were glued by means of phenol resorcinol formaldehyde. These finger joint specimens were profiled so that the test zone had a neck area of 30 x 22,5 mm. Fears were expressed that full sized finger joint test specimens would have a lower strength than smaller profiled specimens. To ascertain whether a width factor could be found, full sized finger joints were tested. No size effect could be discerned as the mean strength of the full sized specimens and that of the smaller specimens was very similar. However, experimental difficulty was found with the testing of full sized specimens with the result that the sample size was small. This small sample size made it difficult to determine the correlation between the modulus of elasticity of the timber and the finger joint strength.

The supposition, that failure of a finger joint in the outer tensile laminate of a beam or laminated tensile member would cause delamination of the failed laminate, was based on observations, fracture mechanics and the results obtained from the tests for shear strength and tensile strength vertical to the grain.

Various sources have observed that boards with defects, such as knots and finger joints, appear to be stronger by a factor of between 1,2 and 1,3 when contained by boards on either side of the defect. This containment factor was built into the simulation model and the effect of the variation of the containment factor was observed. As the strength of beams with a containment factor of 1,2 was less than the strength of beams with a containment factor of 1,3 by about 6%, the conservative value of 1,2 was used for all simulation of beam strength. No containment factor was used for the three laminate tensile member.

Board lengths in all the simulations were assumed to be normally distributed. Lengths are more likely to be fairly random within certain tolerances. It was felt that the assumption of boards having a normal distribution would not influence the results of the simulation dramatically.

The simulation model requires a method to simulate positively correlated values for modulus of elasticity, strength of boards and strength of finger joints. The method used in this study requires that the parameters to be simulated should have a normal or log-normal distribution. This condition could not be met by all three parameters simultaneously. The board strength had a log-normal distribution while modulus of elasticity and finger joint strength were normally distributed. Where all three parameters were used, log-normal distributions were assumed and where only finger joint strength and modulus of elasticity were used, normal distributions were assumed.

The correlation coefficient between modulus of elasticity and timber strength and between modulus of elasticity and finger joint strength was determined experimentally. No experimental results of correlation between finger joint strength and board strength were available. However, it was felt that a fairly high correlation would be found so that the assumed value of 0,7 for the correlation coefficient does not seem excessive.

8.2. NOTABLE RESULTS OF THE SIMULATIONS.

Brittle fracture theory observes that the more material under maximum stress the greater the probability of a failure initiating defect falling in the volume of high stress becomes. The simulation model should predict this volume effect as the number of finger joints would increase with the volume of the timber under maximum stress.

It was observed that the strength of single tensile members decreased with the length i.e. the number of finger joints. When two laminate tensile members with finger jointed boards were simulated, a similar reduction in strength was found as the number of finger joints increased. Two laminate tensile members without finger joints also showed a decrease in permissible stress over that of single members. This is due to the fact that the correlation between tensile strength and modulus of elasticity is not good and that the strength of the timber does not increase in the same ratio as the stiffness increases. From these observations it can be concluded that no increase in stress due to load sharing can be assumed and that in fact a reduction in permissible stress should be made for two laminate members with finger joints that are manufactured from the *E grandis* from the Politsi area.

Size effects were found with the simulation of beam elements and these size effects showed good agreement with size effects found by Madsen et al[8.2] and those prescribed by CP 112[8.1]. These size effects were divided into the three main components, namely depth effect, loading effect and length effect. Provision for the reduction of permissible stress due to depth effect could be made by using a modified version of the formula given in CP 112. The loading effect is not that critical as most beams are subjected to uniformly distributed loads or point loads. Where beams are subjected to equal end moments, a stress reduction factor should be applied. The length effect should be seen as a distance- between- finger- joints effect and does not necessarily only apply to long beams. Short beams with small distances between finger joints can show the same reduction in strength as long beams with large distances between finger joints. A formula for length effect should be based on the number of finger joints in the tension laminates and not on the actual length of the beam.

In conclusion it must be stated that although the simulation method has shortcomings it does point out that there is a volume effect, that this volume effect shows good agreement with the findings of others and that it must be taken into account. Furthermore, the simulation can be used by manufacturers of laminated *E grandis* tensile and flexural elements to predict the strength of their products so that these can be proof loaded for quality control.

8.3 REFERENCES:

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APPENDIX

```
Program Tension;

(* This program is designed to simulate single laminate tension *)
(* members with finger joints                                    *)

Uses
   Graph, Crt, Dos, Printer;

Const
   Board = 600;
   Pi    = 3.141592654;

Type
   List      = Array[1..Board] of Real;

Var
   NormLen, NormStrength                          : List;
   Data                                           : List;
   I, J, K, NoOfBoards, FingNum                   : Integer;
   Length, StdDevLength, Strength, StdDevStrength : Real;
   CutLength, Position, Extrabit, Nextbit         : Real;
   BoardLength, T, Tmin                           : Real;
   FilName                                        : String[13];
   OutFile                                        : Text;

(* Procedure to generate random numbers *)
(* in the range 0 to 1.                 *)
Procedure Rand( var Data : List);
   Var
     I    : Integer;

   Begin
     (* Random number generating function *)
     Randomize;
     For I := 1 to Board do
      begin
      Data[I] := Random(10000) / (10000);
      end;
   End; {Rand}

(* Procedure to normalize the generated random numbers *)
Procedure Normalize( var Data : List );
   Var
     S, Temp1, Temp2     : Real;

   Begin
     For I := 1 to (Board-1) do
       begin
         Temp1 := Data[I];
         Temp2 := Data[I+1];
         Data[I] := (sqrt(-2*Ln(Temp1))) * (cos(2*Pi*Temp2));
       end; {For}

   End; {Normalize}
```

```
(* Procedure to clear the input area of the screen *)
Procedure ClearInput;
   Begin
     GoToxy(2,5);
     Write('                                                            ');
     GoToxy(2,6);
     Write('                                                            ');
     GoToxy(2,5);
   End; {ClearInput}

(* Main Program *)
(* ============ *)

BEGIN
ClrScr;

(**)
(* Create database *)
(* Open file to receive output *)
   ClearInput;
   GoToxy(2,5);
   Write('Specify the output filename (Default is A:**.PRN) : ');
   Read(FilName);

(* Enter the extension *)
   FilName := 'A:' + Filname + '.PRN';
   Assign(OutFile, FilName);
   Rewrite(outFile);

(* Enter parameters to be used in program *)
(* enter the number of boards *)

   ClrScr;
   GoToxy(2,5);
   Write(' Enter the number of boards   :');
   Readln(NoOfBoards);

   ClearInput;
   Write(' Enter the cut length of the tension member  (mm): ');
   Readln(CutLength);
   Writeln(OutFile,'Cut Length    :',CutLength:7:2);

   ClearInput;
   Write(' Enter the average board length  (mm): ');
   Readln(BoardLength);
   Write(' And the standard deviation (mm): ');
   Readln(StdDevLength);
   Writeln(OutFile,'Average Board Length   :  ',BoardLength:7:2);
   Writeln(OutFile,'Std Dev of Length      :  ',StdDevLength:7:2);

   ClearInput;
   Write(' Enter the average Finger joint strength  (MPa): ');
   Readln(Strength);
```

```
   Write(' And the standard deviation  (MPa): ');
   Readln(StdDevStrength);
   Writeln(OutFile,'Average Finger joint strength  :  ',Strength:7:2);
   Writeln(OutFile,'Std Dev of Strength            :  ',StdDevStrength:7:2);

(* Generate enough boards for storage *)
(* Initialize the storage array       *)

      ClearInput;
      Writeln('Normalizing parameters for boards ');
(* Normalize board lengths *)
      Rand(Data);
      Normalize(Data);
      For I := 1 to Board do
        begin
          NormLen[I] := Data[I] * StdDevLength + BoardLength;
        end; {For I}

(* Normalize finger joint strength *)
      Rand(Data);
      Normalize(Data);
      For I := 1 to Board do
        begin
          NormStrength[I] := Data[I] * StdDevStrength + Strength;
        end; {For I}

(**)
(* Start to calculate the cut boards *)
   J := 0;
   Extrabit := 0.0;
   Nextbit  := 0.0;

   For I := 1 to NoOfBoards do
     begin
     ClearInput;
     Writeln(' Calculating the strength of board  ',I);
     Position := 0.0;
     T := 0.0;
     Tmin := 9999999.0;
       FingNum := 1;
       If (Extrabit = 0.0) then
          begin
             J := J +1;
             Nextbit := NormLen[J];
          end; {If}
       If (Extrabit > 0.0) then Nextbit := Extrabit;
       While ((Position + Nextbit) < CutLength) do
          begin
            Position := Position + Nextbit;
            T := NormStrength[J];
            If(T < Tmin) then Tmin := T;
            FingNum := FingNum + 1;
            J := J +1;
            Nextbit := NormLen[J];
```

```
          end; {While}
(* Determine bit to carry over *)
       Extrabit := (Position + Nextbit) - CutLength;
       Writeln(OutFile,Tmin:10:4);
     end; {For I}
   Close(OutFile);
end.
```

```
Program TrippleCheck;
      (* Program to check the simulation method for tripple members *)

Uses
   Graph, Crt, Dos, Printer;

Const
   Boards   = 630;
   Pi       = 3.141593;
   MeanE    = 2.7031;
   StdDevE  = 0.19972;
   MeanT    = 1.06827;
   StdDevT  = 0.34521;
   FactE    = 1.06333;

Type
   List                  = Array[1..Boards] of real;

Var
   Data, NormE, Tensile                          : List;
   I, J, K, NoOfReplications                     : Integer;
   Outfile                                       : Text;
   FilName                                       : String[13];
   ParaMeter, StdDev, Delta1, Delta2, Delta3, T1 : Real;

Procedure Rand ( Var Data : List );
   Var
      I     : Integer;

   Begin
      Randomize;
      for I := 1 to Boards do
        begin
          Data[I] := Random(10000) / 10000;
            If (Data[I] <= 0.00000 ) then
              begin
                 Data[I] := Random(10000) / 10000;
              end;
        end;
   End;

(* procedure to normalize values *)
Procedure Normalize( Var Data : List);
  Var
     Temp1, Temp2                : Real;
  Begin
     J := 0;
     For I := 1 to (Boards -1) do
       begin
         Temp1 := Data[I];
         Temp2 := Data[I+1];
         Data[I] := (sqrt(-2*Ln(Temp1))) * (cos(2*Pi*Temp2));
       end;
  End;
```

```
(* Main Program *)
BEGIN
ClrScr;

(* Open File for storing results *)
   GoToXY(2,5);
   Write('Specify the output filename          :     ');
   Read (FilName);

   FilName := 'A:' + FilName + '.PRN';
   Assign(OutFile, FilName);
   Rewrite(OutFile);

(*  Enter the number of Replications *)
   ClrScr;
   GoToXY(2,5);
   Write('Enter the number of replications     :     ');
   Readln(NoOfReplications);

   Rand(Data);
   Normalize(Data);
   For I := 1 to Boards do
      Begin
        NormE[I] := Data[I] * StdDevE + MeanE;
      end;

   Rand(Data);
   Normalize(Data);
   For I := 1 to Boards do
      Begin
        Tensile[I] := Data[I] * StdDevT + MeanT;
      End;

   I := 1;

   While (I < ( 3 * NoOfReplications + 2)) do
     Begin
      Tensile[I] := Exp(FactE * NormE[I] + Tensile[I]);
      Tensile[I+1] := Exp(FactE * NormE[I+1] + Tensile[I+1]);
      Tensile[I+2] := Exp(FactE * NormE[I+2] + Tensile[I+2]);
      NormE[I]   := Exp(NormE[I]);
      NormE[I+1] := Exp(NormE[I+1]);
      NormE[I+2] := Exp(NormE[I+2]);
      Delta1 := Tensile[I]/NormE[I];
      Delta2 := Tensile[I+1]/NormE[I+1];
      Delta3 := Tensile[I+2]/NormE[I+2];
       If (Delta1 < Delta2) and (Delta1 < Delta3) then
         begin
           T1 := Tensile[I]*(1 + NormE[I+1]/NormE[I] + NormE[I+2]/NormE[I]) / 3;
         end;
      If (Delta2 < Delta1) and (Delta2 < Delta3) then
         begin
```

```
          T1 := Tensile[I+1]*(1 + NormE[I]/NormE[I+1] + NormE[I+2]/NormE[I+1]) / 3;
        end;
      If (Delta3 < Delta1) and (Delta3 < Delta2) then
        begin
          T1 := Tensile[I+2]*(1 + NormE[I]/NormE[I+2] + NormE[I+1]/NormE[I+2]) / 3;
        end;
      Writeln(OutFile,T1:10:4);
      I := I + 3;
    End;

  Close(OutFile);

END.
```

```
Program Twotencor;

  (* This program simulates the strength of double laminated finger jointed *)
  (* tensile members with correlated values for E, board and finger joint   *)
  (* strength                                                                *)

Uses
   Graph, Crt, Dos, Printer;


Const
   Boards = 100;
   Max1   = 100;
   Max3   = 8;
   Strength = 1.06825;
   StdDevStrength = 0.34521;
   FingStrength = 1.854149;
   StdDevFing = 0.13176;
   Modulus = 2.7031;
   StdDevModulus = 0.19971;
   FactEStrength = 1.06334;
   FactEFing     = 0.44432;
   FactStrengthFing = 0.47326;

Type
   Tensile               = Array[1..Max1, 1..Max3] of real;
   Where                 = Array[1..2] of Integer;
   List                  = Array[1..Boards] of real;
   Place                 = Array[1..6, 1..8] of real;

Var
   Found                                           : Where;
   T                                               : Array[1..2] of Real;
   T1, T2, T3, CutLength, Length, StdDevLength     : Real;
   TotalLength, ExtraBit, NextBit, Temp            : Real;
   Position, a1, a2, a3, a4, ThisPos, LookPos      : real;
   Find                                            : Boolean;
   Geometry                                        : Tensile;
   I, J, K, N, L, II, LL, LI, LJ, NoOfBoards, O, JJ   : Integer;
   M                                               : Where;
   Data                                            : list;
   NormLength, NormStrength, NormFing, NormMod     : List;
   FilName                                         : String[13];
   OutFile                                         : Text;
   Posi                                            : Place;
   LE                                              : Array[1..2] of Real;
   Replications                                    : Integer;

  (* ***************************************************** *)
  (* Procedure to generate random numbers between 0 and 1 *)
```

```
(* ****************************************************** *)

    Procedure Rand( var Data : List);
      Var
         I    :Integer;
    Begin

    Randomize;
    For I := 1 to Boards do
      begin
        Data[I] := Random(10000) / (10000);
         If (Data[I] <= 0.0000 ) then
           begin
            Data[I] := Random(10000) / (10000);
           end;
      end;
   End;

(* ****************************************************** *)
(*        Procedure to normalize values                   *)
(* ****************************************************** *)

 Procedure Normalize( Var Data : List);
   Var
      S, Temp1, Temp2             : Real;
 Begin
   J := 0;
   For I := 1 to (Boards -1) do
     Begin
       Temp1 := Data[I];
       Temp2 := Data[I+1];
       Data[I] := (sqrt(-2*Ln(Temp1))) * (cos(2*Pi*Temp2));
     End;
 End;

(* ****************************************************** *)
(*                   MAIN PROGRAM                         *)
(* ****************************************************** *)

BEGIN
ClrScr;

(* ****************************************************** *)
(*               Open File for Input                      *)
(* ****************************************************** *)

 GoToXY(2,5);
 Write('Specify the output filename  (Default is A:**.PRN) :    ');
 Read (FilName);

(* ****************************************************** *)
(*               Enter the extension                      *)
(* ****************************************************** *)

 FilName := 'A:' + FilName + '.PRN';
```

```
  Assign(OutFile, FilName);
  Rewrite(OutFile);

 (* **************************************************** *)
 (*           Enter the number of boards               *)
 (* **************************************************** *)

  ClrScr;
  Write('Enter the number of replications :                 ');
  Readln(Replications);

 (* **************************************************** *)
 (*    Enter the cutlength of the tension member       *)
 (* **************************************************** *)

  Write('Enter the cutlength of the member :                ');
  ReadLn(CutLength);

 (* **************************************************** *)
 (*    Enter the average length of the boards          *)
 (* **************************************************** *)

  Write('Enter the average board length in mm :             ');
  ReadLn(Length);
  Write('and the standard deviation in mm :                 ');
  ReadLn(StdDevLength);

 (* **************************************************** *)
 (* Break the number of replications into units of ten *)
 (* **************************************************** *)

NoOfBoards  := Replications div 10;
For JJ := 1 to NoOfBoards do
 begin

 (* **************************************************** *)
 (* Normalising the finger joint strength              *)
 (* and board strength                                 *)
 (* Clear the data file                                *)
 (* **************************************************** *)

  For I := 1 to Max1 do begin
    For k := 1 to Max3 do begin
      Geometry[I, K] := 0.0;
    end;
  end;

 (* **************************************************** *)
 (*       Generate Randomised board lengths            *)
 (* **************************************************** *)

  Rand(Data);
  Normalize(Data);
  For I :=  1 to Boards do
    begin
```

```
    NormLength[I] := Data[I] * StdDevLength + Length;
  end;

(* **************************************************** *)
(*        Generate Random Board strengths               *)
(* **************************************************** *)

 Rand(Data);
 Normalize(Data);
 For I := 1 to Boards do
   begin
     NormStrength[I] := Data[I] * StdDevStrength + Strength;
   end;

(* **************************************************** *)
(*      Generate Random finger joint strengths          *)
(* **************************************************** *)

 Rand(data);
 Normalize(Data);
 For I := 1 to Boards do
   begin
     NormFing[I] := Data[I] * StdDevFing + FingStrength;
   end;

(* **************************************************** *)
(*      Generate Random Modulus of elasticity           *)
(* **************************************************** *)

 Rand(Data);
 Normalize(Data);
 For I := 1 to Boards do
   begin
     NormMod[I] := Data[I] * StdDevModulus + Modulus;
   end;

(* **************************************************** *)
(* Calculate the geometry of the laminated member       *)
(* which is later cut into the individual members       *)
(* **************************************************** *)

TotalLength := CutLength * 11;
ExtraBit := 0.0;
NextBit  := 0.0;
J := 0;
For I := 1 to 2 do
  Begin
  K := 1;
     Position := 0.0;
     If (ExtraBit = 0.0) then
       begin
          J := J +1;
          NextBit := NormLength[J];
       end;
     If (ExtraBit > 0.0) then NextBit := ExtraBit;
```

```
      While ((Position + NextBit) < (TotalLength + NextBit)) do
        begin
          Position := Position + NextBit;
          Temp     := NormMod[J];                                                          { Modulus of elastic
          Geometry[k, 4*I-3] := Exp(Temp);
          Geometry[k, 4*I-2] := Position;                                                  { Finger joint posit
          Temp     := FactEStrength * NormMod[J] + NormStrength[J];
          Geometry[k, 4*I-1] := Exp(Temp);                                                 { Strength of the bo
          Temp := FactEFing * NormMod[J] + FactStrengthFing * NormStrength[J] + NormFing[J];
          Geometry[k, 4*I]   := Exp(Temp);                                                 { Finger joint stren

           If (k > 1 ) then
             begin
               If(Geometry[k-1, 4*I] > Geometry[k, 4*I]) then
                 begin
                   Geometry[k-1, 4*I] := Exp( FactEfing * NormMod[J] + FactStrengthFing * NormStrength[J] + Norm
                 end;
             end;

          J := J + 1;
          K := K + 1;
          NextBit := NormLength[J];
        end; { While }
      ExtraBit := (Position - TotalLength);
    end; { For }

J := 1;
K := 1;

  (* **************************************************** *)
  (* Long member is cut into shorter tensile members      *)
  (* Determine finger joint positions if any              *)
  (* **************************************************** *)

For II := 1 to 10 do
  begin

  for N := 1 to 6 do begin
    for O := 1 to 8 do begin
      Posi[N,O] := 0.0000;
    end;
  end;

    M[1] := 0;
       If (Geometry[J,2] >= CutLength * II) then
         begin
           M[1] := M[1] + 1;
           Found[1] := 0;
```

```
        Posi[M[1],1] := CutLength;                                      { Position of finger
        Posi[M[1],2] := Geometry[J,3];                                  { Strength of board
        Posi[M[1],3] := Geometry[J,1];                                  { Modulus of elastic
        Posi[M[1],4] := Geometry[J,3];                                  { Strength of board
      end;
    While ( Geometry[J,2] < Cutlength * II ) do
      begin
        M[1] := M[1] + 1;
        Found[1] := 1;
        If (II = 1) then Posi[M[1],1] := Geometry[J,2]                  { Position of finger
            else Posi[M[1],1] := Geometry[J,2] - CutLength * (II-1);
        Posi[M[1],2] := Geometry[J,4];                                  { Finger joint stren
        Posi[M[1],3] := Geometry[J,1];                                  { Modulus of elastic
        Posi[M[1],4] := Geometry[J,3];                                  { Board strength
        J := J +1;
      end;
   Posi[M[1]+1,1] := CutLength;                                         { Values at end of m
   Posi[M[1]+1,2] := Geometry[J,3];
   Posi[M[1]+1,3] := Geometry[J,1];
   Posi[M[1]+1,4] := Geometry[J,3];
 M[2] := 0;
   If ( Geometry[K,6] >= CutLength * II) then
     begin

       M[2] := M[2] + 1;
       Found[2] := 0;
       Posi[M[2],5] := CutLength;
       Posi[M[2],6] := Geometry[K,7];
       Posi[M[2],7] := Geometry[K,5];
       Posi[M[2],8] := Geometry[K,7];
     end;
   While ( Geometry[K,6] < CutLength * II) do
     begin
       M[2] := M[2] + 1;
       Found[2] := 1;
       Posi[M[2],6] := Geometry[K,8];
       If (II = 1) then Posi[M[2],5] := Geometry[K,6]
         else Posi[M[2],5] := Geometry[K,6] - CutLength * (II-1);
       Posi[M[2],7] := Geometry[K,5];
       Posi[M[2],8] := Geometry[K,7];
       K := K + 1;
     end;
   Posi[M[2]+1,5] := CutLength;
   Posi[M[2]+1,6] := Geometry[K,7];
   Posi[M[2]+1,7] := Geometry[K,5];
   Posi[M[2]+1,8] := Geometry[K,7];
```

```
(* ***************************************************** *)
(* Calculate the minimum strength in the laminates      *)
(* for member with no finger joints                     *)
(* ***************************************************** *)

If (Found[1] = 0) and (Found[2] = 0) then
  begin
    T[2] := Posi[1,2]/Posi[1,3] * Posi[1,7];
     T[1] := Posi[1,6]/Posi[1,7] * Posi[1,3];
      If (T[1] <= Posi[1,2]) and (T[2] > Posi[1,6]) then T1 := (Posi[1,6] + T[1])/2;
      If ( T[1] > Posi[1,2]) and (T[2] < Posi[1,6]) then T1 := (Posi[1,2] + T[2])/2;
  end;

(* ***************************************************** *)
(*'Calculate the minimum strength in the member         *)
(* with a finger joint in one of the laminates          *)
(* ***************************************************** *)

If (Found[1] = 0) and (Found[2] = 1) then
  begin
    T[2] := Posi[1,2]/Posi[1,3] * Posi[1,7];
    T[1] := Posi[1,6]/Posi[1,7] * Posi[1,3];
      If (Posi[2,7] > Posi[1,7]) then T[1] := Posi[1,6]/Posi[2,7] * Posi[1,3];
       If (T[1] <= Posi[1,2]) and (T[2] > Posi[1,6]) then T1 := (Posi[1,6] + T[1])/2;
       If ( T[1] > Posi[1,2]) and (T[2] < Posi[1,6]) then T1 := (Posi[1,2] + T[2])/2;
    LL := 2;
   While (Posi[LL,5] < CutLength) do
     begin
        T[2] := Posi[1,2]/Posi[1,3] * Posi[LL,7];
        T[1] := Posi[LL,6]/Posi[LL,7] * Posi[1,3];
         If (Posi[LL+1,7] > Posi[LL,7]) then T[1] := Posi[LL,6]/Posi[LL+1,7]*Posi[1,3];
          If (T[1] <= Posi[1,2]) and (T[2] > Posi[LL,6]) then T2 := (Posi[LL,6] + T[1])/2;
          If ( T[1] > Posi[1,2]) and (T[2] < Posi[LL,6]) then T2 := (Posi[1,2] + T[2])/2;
          If (T2 < T1 ) then T1 := T2;
        LL := LL + 1;
     end;
  end;

(* ***************************************************** *)
(* Calculate the minimum strength in the member         *)
(* with a finger joint in one of the laminates          *)
(* ***************************************************** *)

If (Found[1] = 1) and (Found[2] = 0) then
  begin
    T[2] := Posi[1,2]/Posi[1,3]*Posi[1,7];
```

```
  T[1] := Posi[1,6]/Posi[1,7]*Posi[1,3];
   If (Posi[2,3] > Posi[1,3]) then T[2] := Posi[1,2]/Posi[2,3]*Posi[1,7];
     If (T[1] <= Posi[1,2]) and (T[2] > Posi[1,6]) then
         T1 := (Posi[1,6] + T[1])/2;
     If ( T[1] > Posi[1,2]) and (T[2] < Posi[1,6]) then
       T1 := (Posi[1,2] + T[2])/2;
   LL := 2;
 While Posi[LL,1] < CutLength do
     Begin
       T[2] := Posi[LL,2]/Posi[LL,3]*Posi[1,7];
       T[1] := Posi[1,6]/Posi[1,7]*Posi[LL,3];
        If (Posi[LL+1,3] > Posi[LL,3]) then T[2] := Posi[LL,2]/Posi[LL+1,3]*Posi[1,7];
         If (T[1] <= Posi[LL,2]) and (T[2] > Posi[1,6]) then
            T2 := (Posi[1,6] + T[1])/2;
         If ( T[1] > Posi[LL,2]) and (T[2] < Posi[1,6]) then
            T2 := (Posi[LL,2] + T[2])/2;
         If (T2 < T1 ) then T1 := T2;
     end;
end;

(* ***************************************************** *)
(* Calculate member with at least one finger joint      *)
(* in each laminate.                                     *)
(* Up to five finger joints can be accomodated          *)
(* ***************************************************** *)

If (Found[1] = 1) and (Found[2] = 1) then
 begin
  T1 := 9999.0;
  L := 2;
  For I := 1 to 2 do
   begin
       N := 1;
       While ( N <= M[I] ) do
         begin
           LookPos := Posi[N,4*I-3];
             LE[I] := 1.00 / Posi[N,4*I-1];
           Find := False;
           O := 0;
           While ( Not Find ) do
             begin
              O := O + 1;
               ThisPos := Posi[O,4*L-3];
               If ( ThisPos > LookPos ) then
                begin
                  LE[L] := 1.00 / Posi[O,4*L-1];
                  Find := True;
                end;  {if}
               If ( ThisPos <= LookPos) then
                begin
                    LE[L] := 1.00 / Posi[O,4*L-1];
                end; {if}
             end; {while}
```

```
            T[I] := Posi[O,4*L] * LE[L]/LE[I];
            T[L] := Posi[N,4*I-2] * LE[I]/LE[L];
            If (T[I] <= Posi[N,4*I-2]) and (T[L] > Posi[O,4*L]) then
              T2 := Posi[O,4*L]*(1 + LE[L]/LE[I])/2;
            If (T[I] > Posi[N,4*I-2]) and ( T[L] < Posi[O,4*L]) then
              T2 := Posi[N,4*I-2]*(1 + LE[I]/LE[L])/2;
            N := N + 1;
            If ( T2 < T1 ) then T1 := T2;
          end; {while}
        L := L -1;

  end; {for I = 1 to 2}
 end; {If Found}

  (* ****************************************************** *)
  (*           Store results in the output file            *)
  (* ****************************************************** *)

writeln(OutFile,T1:10:3);
end; {for II}
Writeln(10*JJ:10);
end; {For JJ}
 Close(OutFile);
END. {Main program}
```

```
Program  Beamsim;

  (* ****************************************************************** *)
  (* This program is designed to simulate the profiles of              *)
  (* laminated beams at the location of finger joints along the        *)
  (* length of the beam and to calculate the strength .                *)
  (* ****************************************************************** *)

  Uses
    Graph, Crt, Dos, Printer;

  Const
    MOE               = 15.233;
    StdDevMOE         = 3.2;
    Strength          = 22.09;
    StdDevStrength    = 8.482;
    CoeffES           = 0.93937;
    InterCoeff        = 1.2;
    Board             = 410;
    Max               = 200;
    Max1              = 40;
    Max2              = 20;
    Max3              = 8;

  Type
    List      = Array[1..Board] of Real;
    Beam      = Array[1..Max1, 1..Max2, 1..Max3] of Real;
    Lam       = Array[1..Max] of Integer;

  Var
    Normlen, NormMOE, NormStrength          : List;
    Data                                    : List;
    Year, Day, Month, DayOfWeek             : Word;
    Hour, Minute, Second, Sec100            : Word;
    Geometry                                : Beam;
    FingerPosition                          : Lam;
    Found                                   : Boolean;
    C                                       : Char;
    I, J, K, LamNum, FingNum, NoOfLams      : Integer;
    Option, Ep, II, Times, IK, Replications : Integer;
    BoardLength, StdDevLength               : Real;
    Extrabit, Nextbit, Temp                 : Real;
    BeamLength, Position, Adds, LamThickness : Real;
    NAPosition, LookPos, ThisPos, M         : Real;
    Mmin, SigmaEy, SigmaE, EI, TempEI       : Real;
    E, Why, FJStrength                      : Array[1..40] of Real;
    InFile, OutFile                         : Text;
    FilName                                 : String[14];
    Header                                  : String[20];
```

```
Label
  Chooseys, One, Two, Three, Four, Quit;


(* ******************************************************************* *)
(* Start of the procedure declarations                                 *)
(* ******************************************************************* *)

(* ******************************************************************* *)
(* Procedure to clear the input area of Screen                         *)
(* ******************************************************************* *)

Procedure ClearInpt;
  Begin
    Gotoxy(2,5);
    Write('                                                              ');
    Gotoxy(2,6);
    Write('                                                              ');
    Gotoxy(2,5);
  End;{ClearInpt}


(* ******************************************************************* *)
(* Procedure to generate random numbers in the range of 0 to 1         *)
(* ******************************************************************* *)

Procedure  Rand( var Data : List);
  Var
    I    : Integer;

  Begin
    (* Random number generating function *)
    Randomize;
    For I := 1 to Board do Data[I] := Random(10000) / 10000;
  End;{Rand}


(* ******************************************************************* *)
(* Procedure to normalize the generated random numbers                 *)
(* ******************************************************************* *)
```

```
Procedure Normalize( var Data : List);

  Var
    S, Temp1, Temp2      : Real;

  Begin
    J := 0;
    For I := 1 to (NoOfLams*10) do
      begin
        Temp1 := Data[I];
        Temp2 := Data[I+1];
        S := sqr(2*(Data[I]-1)) + sqr(2*(Data[I+1]-1));
        J := J + 1;
        If (S < 1.000) then
          begin
            Data[J]   := (2*(Temp1-1)) * sqrt(-(2/S) * Ln(S));
          end
          else
            J := J - 1;
      end;{For}

  End;{Normalize}

(* ****************************************************************** *)
(* Procedure for equal end moments                                     *)
(* ****************************************************************** *)

  Procedure Equal;
     begin
       M := (Geometry[I,FingNum,4] * EI) / ((NAPosition - (I-1)*LamThickness) * E[I]);
       M := M * 6 / sqr(NoOfLams*LamThickness);
     end;


(* ****************************************************************** *)
(* Procedure for Four Point loading                                    *)
(* ****************************************************************** *)

  Procedure FourP;
     begin
       M := (Geometry[I,FingNum,4] * EI) / ((NAPosition - (I-1)*LamThickness) * E[I]);
       M := M * 6 / sqr(NoOfLams*LamThickness);
            If (LookPos < BeamLength/3) then  M := M *BeamLength/( 3 * LookPos);
              If (LookPos >= BeamLength/3) or (LookPos < 2*beamLength/3) then M := M;
```

```
            If (LookPos >= 2*BeamLength/3) then  M := M * BeamLength /( 3 * (BeamLength-LookPos));

    end;

(* ******************************************************************* *)
(* Procedure for uniform loading                                       *)
(* ******************************************************************* *)

  Procedure UniLoad;
    begin
      M := (Geometry[I,FingNum,4] * EI) / ((NAPosition - (I-1)*LamThickness) * E[I]);
      M := M * 6 / sqr(NoOfLams*LamThickness);
      M := M * sqr(BeamLength)/(4 * (BeamLength * LookPos - sqr(LookPos)));
    end;

(* ******************************************************************* *)
(* Procedure for Central point load                                    *)
(* ******************************************************************* *)

  Procedure CenPoint;
    begin
      M := (Geometry[I,FingNum,4] * EI) / ((NAPosition - (I-1)*LamThickness) * E[I]);
      M := M * 6 / sqr(NoOfLams*LamThickness);
          If (LookPos < BeamLength/2) then  M := M * BeamLength/( 2 * LookPos);
            If (LookPos >= BeamLength/2) then  M := M * BeamLength /( 2 * (BeamLength-LookPos));

    end;


(* ******************************************************************* *)
(* Procedure which draws the intro logo on the screen                  *)
(* ******************************************************************* *)

  Procedure Logo;

   Var
     M,N,I                      : Integer;
     C                          : Char;

   Begin
     {░▒▓│┤╡╢╖║┐┘└┌┴┬├─┼┬█▄▌▐▀·•}
```

```
Clrscr;
M := 4;
N := 2;
TextBackground(Black);
TextColor(Blue);
Gotoxy(m  ,n   ); Write('┌──────────────────────────────────────────────────────────────────────┐');
Gotoxy(m+1,n+1 ); Write('█▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀▀█');
Gotoxy(m+1,n+21); Write('█▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄▄█');
Gotoxy(m  ,n+23); Write('└──────────────────────────────────────────────────────────────────────┘');
For I := 1 to 21 do
  begin;
      Gotoxy(m   ,n+I); Write('│ █');
      Gotoxy(m+71,n+I); Write('█ │');
  end;{For}
  Gotoxy(m   ,n+22); Write('│  ');
  Gotoxy(m+71,n+22); Write('  │');


{Draw laminated beam}
TextColor(Yellow);
Gotoxy(m+5,n+16); Write('░░░│░░░░░░░░░░░░░░░░│░░░░░░░░░░░░░░░░░░░░░░│░░░░░░░░░░');
Gotoxy(m+5,n+17); Write('▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒│▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒│▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒▒');
Gotoxy(m+5,n+18); Write('░░░░░░░░░░░│░░░░░░░░░░░░░░░░░░░│░░░░░░░░░░░░░░░░░░░░░░░░│░░');
Gotoxy(m+5,n+19); Write('    Ω                                              Ω ');

{Box title}
TextColor(White);
Gotoxy(m+11,n+3);Write('┌─────────────────────────────────────────────┐');
Gotoxy(m+11,n+4);Write('│    TIMBER BEAM PROFILE SIMULATION PROGRAM    │ ');
Gotoxy(m+11,n+5);Write('│               Version 1.00                   │ ');
Gotoxy(m+11,n+6);Write('│               Developed by                   │ ');
Gotoxy(m+11,n+7);Write('│               W.M.G BURDZIK                  │ ');
Gotoxy(m+11,n+8);Write('│         DEPT. OF CIVIL ENGINEERING           │ ');
Gotoxy(m+11,n+9);Write('│           UNIVERSITY OF PRETORIA             │ ');
Gotoxy(m+11,n+10);Write('│                PRETORIA                     │ ');
Gotoxy(m+11,n+11);Write('│                                             │ ');
Gotoxy(m+11,n+12);Write('│            Tel. (012) 420-2175              │ ');
```

```
    Gotoxy(m+11,n+13);Write('└──────────────────────────────────────┘ ');

    TextColor(Magenta);
    Gotoxy(30 ,25);
    Write('Press any key to continue');
    Gotoxy(8  ,25);
    GetDate(Year, Day, Month, DayOfWeek);
    GetTime(Hour, Minute, Second, Sec100);
    Write(Year,'-',Day,'-',Month);
    Gotoxy(65,25);
    Write(Hour:2,':',Minute:2,':',Second:2);
    Gotoxy(m+2,n+21);
    C := Readkey;
  End;{Logo}


(* ****************************************************************** *)
(* Procedure which draws a frame around the perimeter of screen      *)
(* ****************************************************************** *)

  Procedure Frame1;
    Var
      II           : Integer;

    Begin
      Clrscr;
      TextColor(Blue);
      Gotoxy(8,25);
      GetDate(Year, Day, Month, DayOfWeek);
      GetTime(Hour, Minute, Second, Sec100);
      Write(Year,'-',Day,'-',Month);
      Gotoxy(65,25);
      Write(Hour:2,':',Minute:2,':',Second:2);
      Gotoxy(2,1 ); Write('┌──────────────────────────────────────────────────────────┐');
      Gotoxy(2,12); Write('└──────────────────────────────────────────────────────────┘');
      For II := 2 to 11 do
        begin
          Gotoxy(2 ,II); Write('│');
          Gotoxy(77,II); Write('│');
        end;{For}
    End;{Frame1}


(* ****************************************************************** *)
(* Procedure which allows you to choose an option                     *)
(* ****************************************************************** *)
```

```
Procedure Choose(Var  Option : Integer);
  Var
    I,J,K,Iold,Inew,Choices  : Integer;
    Title                    : Array[1..10] of String[35];
    MsxOut                   : Text;
    LastOpt,Opt              : Integer;

  Label
    Restart, Sorry, Finish, Beginning;



Procedure Frame;
  Var
    I          : Integer;

  Begin
    TextBackground(Black);
    Textcolor(Blue);
    GetDate(Year, Day, Month, DayOfWeek);
    GetTime(Hour, Minute, Second, Sec100);
    Gotoxy(8 ,25);
    Write(Year,'-',Day,'-',Month);
    Gotoxy(65,25);
    Write(Hour:2,':',Minute:2,':',Second:2);
    Gotoxy(2 ,1 ); Write('┌──────────────────────────────────────────────────────────────────────────┐');
    Gotoxy(2 ,21); Write('└──────────────────────────────────────────────────────────────────────────┘');
    For I := 2 to 20 do
      begin
        Gotoxy(2 ,I); Write('│');
        Gotoxy(77,I); Write('│');
      end;{For}

    TextColor(Red);
    Gotoxy(27,2); Write('┌──────────────────┐');
    Gotoxy(29,3); Write('    B E A M ');
    Gotoxy(27,4); Write('└──────────────────┘');
    Gotoxy(27,3); Write('│');
    Gotoxy(46,3); Write('│');
    Gotoxy(48,3); Write(#249);
    Gotoxy(25,3); Write(#249);
    Textcolor(Black);
    Textbackground(Lightgray);
    Gotoxy(20,5); Write(' Laminated Beam Profile Program ');
    Textcolor(White);
    Textbackground(Black);
    Gotoxy(10,22);
    Write('Press a Letter to Select Option :: Press ');
    Textcolor(Black); Textbackground(Lightgray);
    Write(' <ENTER> ');
    Textcolor(White);Textbackground(Black);
    Write(' for Choice');
  End;{Frame}
```

```
Procedure OptionLabel(I : Integer);
  Begin
    If(I = 2*Trunc(I/2)) Then J := 37 Else J := 7;
    K := Trunc((I/2) + 0.6);
    Gotoxy(J,5+2*K);
    Write(Title[I]);
    Gotoxy(1,25);
  End;


Procedure Change;
  Begin
    OptionLabel(Iold);
    Textcolor(Black);
    Textbackground(White);
    OptionLabel(Inew);
    Textcolor(White);
    Textbackground(Black);
    Iold := Inew;
  End;{Change}


Procedure GetKey;
  Var  C  : Char;

  Begin
    Repeat
    C := ReadKey;
    Case C of
      #13      : Inew := 0;
      #65,#97  : Inew := 1;
      #66,#98  : Inew := 2;
      #67,#99  : Inew := 3;
      #68,#100 : Inew := 4;
      #69,#101 : Inew := 5;
      #81,#113 : Inew := 6;
    end;{Case}

    If Inew > 0 Then  LastOpt := Inew;

    If (C = #27) and Keypressed then
      begin
        C := ReadKey;
        Case C of
          #71 : Inew := 1;
          #72 : If Iold > 2 then Inew := Iold - 2
                Else
                  If Iold = 1 then Inew := Choices-1
                     Else Inew := Choices;

          #73 : Inew := 2;
          #75 : If Iold > 1 then Inew := Iold-1
                Else Inew := choices;
```

```
        #77 : If Iold < Choices then Inew := Iold+1
              Else Inew := 1;

        #79 : Inew := Choices-1;
        #80 : If Iold < Choices-1 then Inew := Iold+2
              Else
                If Iold = Choices-1 then  Inew := 1 else Inew := 2;

        #81 : Inew := Choices;
        #113: Inew := 2;
      end;{Case}
      LastOpt := Inew;
    end;{If}

  Until Inew <> Iold;
end;{Getkey}


Begin;
  Beginning:
    LastOpt := 1;
    ClrScr;
    Frame;
    Choices  := 6;
    Title[1] := ' A. Beam equal end moments  ';
    Title[2] := ' B. Beam four point loading ';
    Title[3] := ' C. Beam uniform loading ';
    Title[4] := ' D. Beam Central point load ';
    Title[5] := ' E.                          ';
    Title[6] := ' Q. Quit                     ';

    For I := 1 to Choices do OptionLabel(I);
    Iold := 1;
    Inew := 1;
    Change;

  Restart :
    Repeat
      GetKey;
      If inew > 0 then Change;
    Until Inew = 0;
    If LastOpt = 6 then Clrscr;
    If LastOpt = 5 then Goto Sorry;
    Option := LastOpt;
    Clrscr;
    Goto Finish;

  Sorry:
    Gotoxy(15,15); Textcolor(Black); Textbackground(Lightgray);
    Write( 'This particular option is not yet available !');
    Gotoxy(1,25);
    Textcolor(Black); Textbackground(Black);
    Delay(5000);
    Goto Beginning;
```

```
    Finish:
  end;{Choise}

(* ******************************************************************** *)
(* End of procedure declarations                                        *)
(* ******************************************************************** *)

                              (* * *)

(* ******************************************************************** *)
(*                          MAIN PROGRAM                                *)
(* ******************************************************************** *)

 BEGIN
   (* Display the logo on screen *)
   Logo;
   (* Choose which part of program to execute *)
   Chooseys :
     Choose(Option);

   (* Branch according to the choice made *)
   Case Option of
     6 : Goto Quit;
   End;{Case}

(* ******************************************************************** *)
(* Create new beam database                                             *)
(* This is achieved by getting a specified length of beam as            *)
(* well as number of laminates from user and building the beams         *)
(* and then writing them to a user supplied filename                    *)
(*                                                                      *)
(* Open the user supplied for file to receive output                    *)
(* so that it can be read into a LOTUS 123 File or                      *)
(* Statgraphics file for easy manipulation                              *)
(* ******************************************************************** *)

     ClearInpt;
     Gotoxy(2,5);
```

```
     Write('Specify the output filename (Default is A:*.PRN) : ');
     Read(FilName);

(* ******************************************************************* *)
(* Add the extention to the filename                                   *)
(* ******************************************************************* *)

     FilName := 'A:'+ FilName + '.PRN';
     Assign(OutFile, FilName);
     Rewrite(OutFile);

(* ******************************************************************* *)
(* Input the parameters to be used in this program                     *)
(* ******************************************************************* *)

     ClrScr;
     Gotoxy(2,5);
     Write('Enter Length of the BEAMS (mm): ');
     Readln(BeamLength);
     Writeln(OutFile,'Beam Length        :  ',Beamlength:7:2);

     ClearInpt;
     Write('Enter Number of Laminates per Beam : ');
     Readln(NoOfLams);
     Writeln(OutFile,'No of Laminates    :  ', NoOfLams:2);

     ClearInpt;
     Write('Enter Thickness of Laminates : ');
     Readln(LamThickness);
     Writeln(OutFile,'Thickness of Laminates    :  ', LamThickness:7:2);

     ClearInpt;
     Write('Enter the Average BOARD Length (mm): ');
     Readln(BoardLength);
     Write(' And the Standard Deviation (mm): ');
     Readln(StdDevLength);
     Writeln(OutFile,'Avg Board Length   :  ', BoardLength:7:2);
     Writeln(OutFile,'Std Dev            :  ', StdDevLength:5:2);

     ClearInpt;
     Write('Enter the number of replications desired :    ');
     Readln(Replications);

     Writeln(Outfile,'Minimum Profile Values for the simulated beams are : ');

(* ******************************************************************* *)
```

```
(* Repeat the calculations to build the required number of beams    *)
(* ***************************************************************** *)

      For II := 1 to Replications do
        begin

          (* Generate enough boards to build beam *)
          (* Initialize the Geometry arrays *)

          For I := 1 to Max1 do begin
            For J := 1 to Max2 do begin
              For K := 1 to Max3 do begin
                  Geometry[I,J,K] := 0.0;
              end; {For}
            end; {For}
          end; {For}


          ClearInpt;
          Writeln('Normalizing parameters for beam ',II);
          Rand(Data);
          Normalize(Data);
          For I := 1 to (NoOfLams*10) do
            NormLen[I] := Data[I] * StdDevLength + BoardLength;
          {end For}

(* ***************************************************************** *)
(* Calculating normalized Modulus of Elasticity                      *)
(* ***************************************************************** *)

          Rand(Data);
          Normalize(Data);
          For I := 1 to (NoOfLams*10) do
            NormMOE[I] := Data[I] * StdDevMOE  + MOE;
          {end For}

(* ***************************************************************** *)
(* Calculating normalized Finger Joint Strength                      *)
(* ***************************************************************** *)

          Rand(Data);
          Normalize(Data);
          For I := 1 to (NoOfLams*10) do
              NormStrength[I] := Data[I] * StdDevStrength + Strength;
          {end For}
      /
```

```
(* **************************************************************** *)
(* Start to build the beam                                          *)
(* **************************************************************** *)

          Writeln(' Calculating  Beam Geometry');
          Extrabit := 0.0;
          Nextbit  := 0.0;
          J := 0;
          For I := 1 to NoOfLams do
            begin
              Position := 0.0;
              Lamnum := I;
              Fingnum := 1;
              If (Extrabit = 0.0) then
                begin
                  J := J + 1;
                  Nextbit := NormLen[J];
                end;{If}
              If (Extrabit > 0.0) then Nextbit := Extrabit;
              While ((Position+Nextbit) < BeamLength) do
                begin
                  Position := Position + Nextbit;
                  Geometry[Lamnum, Fingnum, 1] := Position;
                  Geometry[Lamnum, Fingnum, 2] := NormMOE[J];
                  Geometry[Lamnum, Fingnum, 3] := NormMOE[J+1];
                  Geometry[Lamnum, Fingnum, 4] := CoeffES * NormMOE[J] + NormStrength[J];
                   If (Lamnum > 1) then Geometry[Lamnum, Fingnum, 4] := InterCoeff * Geometry[Lamnum, Fingnum,
                    Temp := CoeffES * NormMOE[J+1] + NormStrength[J];
                     If (Temp < Geometry[Lamnum, Fingnum, 4]) then Geometry[Lamnum, Fingnum, 4] := temp; }
                  Fingnum := Fingnum + 1;
                  J := J + 1;
                  Nextbit := NormLen[J];
                end;{While}
              (* Determine bit to carry over *)
              Extrabit := (Position + Nextbit) - Beamlength;
            end;{For}

(* **************************************************************** *)
(* Now find the minimum strength value for all fingers in the       *)
(* bottom quarter of of the beam                                    *)
(* **************************************************************** *)

            Times := NoOfLams div 4;
            Adds :=  NoOfLams mod 4;
            If (Adds <> 0.0) then Times := Times + 1;
```

```
          (* The y values being (2*I-1)*Lamthickness/2 respectively *)
          For I := 1 to NoOfLams do
            begin
              Why[I] := (2*I-1)*Lamthickness/2;
            End; {For}

        M := 0.0;
        Mmin := 9999999.0;
        For I := 1 to Times do
          begin
            Fingnum := 1;
            while (Geometry[I, Fingnum, 2] <> 0) do
              begin
                LookPos := Geometry[I, Fingnum, 1];

                SigmaEy := 0.0;
                SigmaE  := 0.0;

(* ****************************************************************** *)
(* Look through layers above to find moduli of elasticity             *)
(* Add them up to find Neutral Axis and flexural stiffness EI         *)
(* ****************************************************************** *)

                For J := 1 to NoOfLams do
                  begin
                    Found := False;
                    K := 1;
                    While ( not Found ) do
                      begin
                        ThisPos := Geometry[J, K, 1];
                        If (ThisPos <= 0.0) then
                          begin
                            E[J] := Geometry[J, K-1, 3];
                            Found := True;
                          end; {If}
                        If (ThisPos >= LookPos) then
                          begin
                            E[J] := Geometry[J, K, 2];
                            Found := True;
                          end; {If}
                        K := K + 1;
                      end; {While}
                  end; {For J}

                E[I] := Geometry[I,Fingnum,2];
                  If (Geometry[I,Fingnum,3] > Geometry[I,Fingnum,2]) then
                    begin
                      E[I] := Geometry[I,Fingnum,3];
```

```
                    end; {If}
(* ****************************************************************** *)
(* The modulus of E and other parameters for each laminate have      *)
(* been found, now use all of these to calculate the modulus of      *)
(* ruptue and ascertain whether it is a minimum                      *)
(* ****************************************************************** *)


                For J := 1 to NoOfLams do
                  begin
                    SigmaE  := SigmaE + E[J];
                    SigmaEy := SigmaEy + E[J] * Why[j];
                  end; {For}
                (* Neutral Axis Position *)
                NAPosition := SigmaEy / SigmaE;

                (* EI *)
                EI := 0.0;
                For J := 1 to NoOfLams do
                  begin
                    TempEI := (E[J] * LamThickness * (sqr(NAPosition - Why[J])));
                    EI     := EI + ((E[J] * (LamThickness*sqr(LamThickness)/12)) + TempEI);
                  end; {For}

(* ****************************************************************** *)
(* Branch according to the choice of loading pattern made            *)
(* ****************************************************************** *)

    Case Option of
      1 : Equal;   {Equal end moments}
      2 : Fourp;   {For point loading}
      3 : Uniload; {Uniform loading}
      4 : CenPoint;  {Central point load}
      6 : Goto Quit;
    End;{Case}

                If (M < Mmin) then Mmin := M;
                Fingnum := Fingnum + 1;
              end;{While}
          end;{For I}

(* ****************************************************************** *)
(* Write the minimum value found to the output file                  *)
```

```
(* ****************************************************************** *)
          Writeln(Outfile,'Beam ',II:3,' = ',Mmin:10:3);

        end;{For II}
(* ****************************************************************** *)
(* All the beams have been profiled, now exit                          *)
(* Close the files used here                                           *)
(* ****************************************************************** *)
        Close(Outfile);
        Write('Output file created, Press any key to return to main menu');
        C := Readkey;
        Goto Chooseys;

    One :
      (* This is a dummy label *)
      Goto Chooseys;

    Two :
      GoTo Chooseys;

    Three :
      GoTo Chooseys;

    Four :
      GoTo Chooseys;

    Quit :

END.{Main Program}
```