DESIGN RECOMMENDATIONS FOR BAMBOO ELEMENTS IN EXPOSED TEMPORARY STRUCTURES

by

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Abstract

Bamboo is widely used for exposed temporary structures such as scaffolding and formwork or falsework supports. However, bamboo elements are neither designed nor proportioned on a logical basis, so that safety of workmen or the structure itself is suspect and there is no scope for either optimal standardisation or provision of custom designed structures. Unless these shortcomings are rectified, bamboo may loose to its main competitor, the steel scaffold tube, thus curtailing the primary utilization potential of a valuable natural resource. Evolution of design recommendations for bamboo can overcome these limitations.

The study dealt with the bamboo species, Bambusa vulgaris, which is widely used in above structures. Test programme was planned to develop the required mechanical properties of bamboo. It consisted of 324 flexural tests, 108 crushing tests, 324 buckling tests and 108 tensile tests as well as specific gravity and moisture content tests on each specimen.

It resulted in formulating design recommendations for bamboo elements in flexure, crushing, buckling or tension as well as modules of elasticity and deflection limit.

1.0 Introduction

Bamboo is a perennial grass that occurs [1] in the natural vegetation of many parts of the tropical, subtropical and mild temperate regions, and although it is a grass it has much in common with a tree [2]. In Sri Lanka, bamboo is very abundant but only fourteen species have been reported [3] to be growing locally. Of these *Bambusa vulgaris* (Kaha una) is the most widely used for temporary structures.

A bamboo plant consists of a rhizome from which shoots grow up. They reach a height of 15 to 20m in 4-8 weeks. Growth is based on longitudinal divisions of cells only [2] and growth in diameter or thickness is absent. After the first 8 weeks, the new culm needs three or four years to become an adult during which branches grow from nodes commencing from top node and polymerisation takes place to get appropriate cellulose and lignin molecules. Once this process is complete the culm is ripe. The first crop takes place after about 6 years, continued by a crop each year for a long period of 20-30 years till it flowers and plant dies.

A bamboo culm looks like a cylinder but it is neither perfectly circular in cross-section nor straight along the length. It has an outer base diameter of 55 - 125 mm, a base wall thickness of 4.5 - 27 mm, and a node spacing of 255 - 380mm.

The culm consists[4] of 40% cellulose fibres for the strength, 50% parenchyma for the matrix and 10% vessels for conducting fluids. Rays do not occur. The outer skin is covered with a layer of cells containing some percentage of silica, and a waxy[1] covering (cutrin) which restricts loss of water, to provide good sealing against the climate. In the radial direction, parenchyma and vessels are more frequent in the inner third of the wall, while in the outer third, percentage of cellulose fibres is higher. In the longitudinal direction, the amount of cellulose fibres increases from bottom to top with the parenchyma content decreasing. The cellulose fibres in bamboo have high ultimate strength[1] and exhibit similar elongation to that of steel before reaching the elastic limit.

Advantages of bamboo are: convenient size and shape for easy handling, clean and hard surface, high strength-to-weight ratio, Diaphragms at nodes prevent local buckling and strengthen nodal zones for concentrated load transfer, strong and hard tissues are concentrated near the outer surface, allows the use of simple cutting tools, less waste as there is no bark to remove, pliability which makes it resistant to strong winds and earthquakes, absence of defects such as knots and slope of grain, and low level of skill required for erection of bamboo structures. The shortcomings are: low durability; shrinkage with drying leads to splitting; efficient jointing difficult due to round form and low longitudinal shear at internodes; presence of silica in the outer tissues[5] dulls blades of cutting tools; varying

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out-of-straightness between culms; difficulty of finding culms of same size, taper and node spacing; and difficulty of nailing without pre-boring.

Although some guidance is available on use of bamboo for scaffolding[6] and formwork structures[7], they rely on considerable generalisations and are no more than rules of thumb. In contrast, standards[8,9] exist for design and construction of metal scaffoldings and falsework. Suitable design loads and structural forms for bamboo structures can be derived from these standards. However, design data on local bamboo elements and their joints can only be developed through local research.

The Department of Labour is concerned about safety of workmen. Increasing use of bamboo temporary structures in construction requires strict enforcement of safety standards by Labour Officers. Present practices are superior to early Chinese scaffolding[10], but some arrangements like the plane frame scaffold for cleaning and painting may not ensure adequate safety. Unless design information on bamboo structures is made available to them, provision of adequate safety to workmen cannot be guaranteed.

Bamboo is an important forest resource which is mostly used for temporary structures in the construction industry. Unless confidence of users is enhanced by provision of detailed information on behaviour of bamboo structures leading to improved performance and cost reduction, bamboos may be replaced by steel scaffold tubes even for short structures, thus leaving a valuable natural resource under-utilized.

Structural behaviour of bamboo is a complex phenomenon as it is influenced by numerous variables. Hence any attempt to quantify structural behaviour depends on working out limits for strength and stiffness in terms of species and physical dimensions, and imposing strict acceptance limits on quality of bamboo like maturity, exposure period after felling, minimum cross-sectional dimensions and tolerances for curvature and other defects like splitting. This process requires extensive research effort and this study on design recommendations of bamboo elements is a step in that direction.

2.0 Objectives

The main objectives of this study are: (a) To evaluate the most important variables that affect mechanical properties of bamboo; (b) To determine the key mechanical properties of *Bambusa vulgaris* and, where applicable, to compare results with previous research on same or similar species of bamboo; and (c) To provide design information for design of bamboo as verticals, ledgers, putlogs or diagonal braces in a temporary structure.

3.0 The Study

3.1 General

For the development of the design information required for temporary bamboo structures, the following tests were conducted: Flexural test, Crushing stress test, Buckling test and Tensile test. In addition moisture content and specific gravity were also measured for each failed specimen.

The parameters or variables affecting structural performance of bamboo are: Species, Age at felling, Period of exposure after felling, Growth condition, Specigic gravity, Moisture content, Disposition of nodes, Position along the culm, Curvature, Diameter and thickness, Modulus of elasticity, Duration of loading, Seasoning, and other Defects. These variables were controlled as stated in succeeding sections.

Test results were converted to design stresses using standard statistical techniques and factors of safety commonly applied to structural timber[26,28]

3.2 Flexural Test

Species of bamboo tested was *Bambusa vulgaris*, as it is the most widely used for temporary structures. Age at felling was kept within the range of 4-6 years by selecting only matured bamboo (brownish-yellow, free of bud scars at nodes, higher density, and free of splits or damages). As the bamboo is not stress-graded in Sri Lanka, timber traders give freedom of selection of bamboo to the buyers. Bamboo was tested within 4-6 weeks of purchase so that effect of period of exposure after felling was made insignificant. Three growth conditions were considered by selecting from three sources which were from the banks of Kelani ganga, Kalu ganga and Bolgoda lake. Specific gravity, moisture content, node spacing, thickness and modulus of elasticity were measured for each specimen, as they cannot be controlled. Position along the culm was considered by taking three specimens from each culm covering top, middle and bottom parts of the culm. Initial curvature was controlled by rejecting any bamboo out of straight by more than one diameter in every 2.0m in accordance with IS10145[11]. Diameter was varied by considering three sizes of bamboo, small (63mm $\leqslant$ d < 72mm), Average (72mm $\leqslant$ d < 88mm) and large (d $\geqslant$ 88mm) in accordance with Samarasinghe[6]. Only short term loading was considered, and design stress for other durations are expected to be obtained using factors given in BS 5268[12]. Bamboos used for this study were well seasoned by allowing moisture evaporation to take place for 4-6 weeks after felling. Test specimens were free of defects (splits, insect holes, surfaces with fungi, excessive curvature, immature bamboo, cuts across grain, scraped surfaces or other damages).

Twelve bamboo culms not less than 6.5m long were selected to represent a growth condition and large size of bamboo. They were each cut in the order of 2.7m, 2.1m and 1.5m; 2.1m, 1.5m and 2.7m; 1.5m, 2.7m and 2.1; etc. from the base of the culm so that for each specimen size different portions of the tapering culm are included. This process was repeated for medium and small sizes of bamboo as well as the remaining two growth conditions. A total of 108 specimens were tested for each specimen length. The specimen lengths 2.7m, 2.1m and 1.5m were made to give clear spans of 2.4m, 1.8m and 1.2m respectively to simulate likely span lengths of putlogs and ledgers in a scaffolding. Each specimen was tested under a mid-span concentrated load with ends simply supported at the respective clear span while recording the load-deformation response. Test procedure resembled that of IS 6874[13] except for dimensions. After failure, specimen was cut at two sections adjacent to failure zone to measure the outer diameter and thickness. Some material was also removed from the failure zone to measure the specific gravity and the moisture content of the specimen.

3.3 Crushing stress test

Variables were controlled as in the flexural test. Specimens with a node were tested as inclusion of a node was found to reduce the strength[14,15]. As node spacing varied from 255 to 380mm, an intermediate round figure of 300mm was used for the length of a specimen and small changes in slenderness ratio of different specimens were not considered adequate to alter the failure mode from crushing to buckling.

Four bamboo culms not less than 6.5m long were selected to represent a growth condition and large size of bamboo. Three test specimens 300mm long inclusive of a centrally placed node were cut from top, middle and bottom of each culm. This process was repeated for medium and small size of bamboo as well as remaining two growth conditions. A total of 108 crushing test specimens were tested. Test procedure resembled that of IS 6874[13] except for dimensions and inclusion of a central node. Measurement of diameter, thickness, specific gravity and moisture content was done similar to 3.2.

3.4 Buckling Test

Variables were controlled as in the flexural test. Specimen length of 1.5m was selected to simulate the vertical of a bamboo scaffolding. In order to study the variation of buckling stress with slenderness ratio, two other specimen lengths of 0.9m and 0.6m were also considered. As diameter and thickness of specimens vary, these three specimen lengths were expected to give adequate variation of slenderness ratio for the above study.

Six bamboo culms not less than 6.5m long were selected to represent a growth condition and large size of bamboo. They were each cut in the order of 1.5, 0.9, 0.6, 1.5, 0.9 and 0.6m; 0.9, 0.6, 1.5, 0.9, 0.6 and 1.5m; 0.6, 1.5, 0.9, 0.6, 1.5 and 0.9m; etc. from the base of the culm so that for each specimen size, different portions of tapering culm are included. This process was repeated for medium and small size of bamboo as well as the remaining two growth conditions. A total of 108 specimens were tested for each specimen length. Each specimen was loaded axially with the central outward deformation measured by two dial gauges placed at right angles to each other. Vertical deformation between the two ends of the specimen were also measured. Measurement of diameter, thickness, specific gravity and moisture content was done similar to 3.2.

3.5 Tensile Test

Variables were controlled as in the flexural test. Specimens with a node were tested as inclusion of a node was found to reduce the strength[2,14,16,17]. Tensile test used bamboo strips 10mm x thickness in cross-section with a gauge length of 125mm and overall length of 200mm with gripping ends 25mm wide.

Four bamboo culms not less than 6.5m long were selected to represent a growth condition and large size bamboo. Three test specimens 200mm long inclusive of a centrally placed node were cut from top, middle and bottom of each culm. Strip of bamboo 25mm wide was split from each such specimen and, using a chisel, saw and file, the strip was cut into the required specimen shape. This process was repeated for medium and small size of bamboo as well as remaining two growth conditions. A total of 108 tensile test specimens were tested. Test procedure for tensile tests was not available even in IS 8242[18], which covered only static bending, compression parallel to grain and shear parallel to grain. Cross-sectional dimensions of the test specimen were measured before testing, while specific gravity and moisture content were measured after failure with material obtained from the vicinity of the failure zone.

4.0 Results and Analysis

4.1 General

This paper draws on three investigations[15,16,19] and some further work on structural behaviour of bamboo. Design information was developed for bamboo using similar principles applied for the evolution of design recommendations for sawn timber from experimental results, as Janssen[2,20,21] and Arce[22] have demonstrated that usual structural theories can be applied to bamboo with suitable modifications.

4.2 Design Flexural Stress

Ultimate flexural stress of a specimen was calculated from its ultimate load, span and section modulus of the bamboo near the failure zone. All these ultimate flexural stresses from different span lengths were pooled together and the values adjusted to the mean specific gravity of 0.60 assuming that flexural stress is directly proportional to the specific gravity. Further, specific gravity of all the test specimens (inclusive of other tests such as compression and tension) ranged from 0.50 to 0.81. The values compared favourably with those reported by Jayantha Manel[14] (0.47-0.74), Siopongco et al[5] (0.46-0.72), Raitt[23] (0.76-0.96) and Janssen[2,20,21] (0.6-0.9).

The next correction done was to bring all the adjusted ultimate flexural stresses to a moisture content of 30%, the fibre saturation point. This was done using the formula:

$$\log S = \log S_p + K(M_p - M)$$

where S is the ultimate flexural stress at the moisture content M, while S_p and M_p are the ultimate flexural stress and the moisture content at the fibre saturation point, k being a constant. No correction was done for any ultimate flexural stresses above fibre saturation point, as in this range, moisture content does not influence the ultimate flexural stress. Moisture content values of flexural tests varied from 19% to 158%, with only a few values below 30%. Finally, the design flexural stress was computed at a statistical exclusion limit of 5 in 100 as recommended in BS 5268 [12], using the formula $f = (f_m - KS)/F$ where f = design flexural stress; f_m = mean ultimate flexural stress; K= statistical constant for 5% exclusion; S = standard deviation of ultimate flexural stress; and F = reduction factor similar to the conventional factor of safety which allows for small errors in moisture content, duration of loading, sectional properties, design assumptions, analysis, and construction tolerances. Wet stresses were derived as bamboo is used structurally most often in temporary exposed structures here. Recommended design flexural stress, other useful measures of observed results, and values of constants[12,25] used in evolution of design information are shown in Table 1. Design flexural stress compared well with those reported by Siopongco et al[5] (9.81) and Janssen[20,24] (12.2). There was no significant correlation between the parameter, Node spacing/diameter (2.92 to 5.97), and flexural stress. External diameter and thickness of test specimens varied from 54.5 to 95.0mm, and 5.0 to 23.0mm respectively.

Data reduction process adopted for the modulus of elasticity was similar to that of flexural stress and the recommended values and other useful information are shown in Table 1. These values compared well with those reported by Samarasinghe[6] (15200), Siopongco et al[5] (5590 to 21180) and Janssen[20,24] (20000). There was no significant correlation between the parameter, node spacing/diameter (2.92 to 5.97), and modulus of elasticity. Coefficient of variation of test results (see Table 1) was within 20% and, hence, satisfactory.

Deflection limit is only vaguely specified for timber structures[12,25] and varies depending on the specific application as well as the specifier. Some noteworthy recommendations for timber structures are: (a) For general purposes CP112[25] has recommended a limit of 0.003L (where L is the simply supported span length); (b) Ozelton and Baird[26] have recommended: (i) L/180 for beams with storage racking with no access or limited access to personnel; (ii) L/240 for storage racking with access for personnel, and (iii) L/240 for roof decking; (c) Karlsen[30] has recommended: (i) L/250 for interstorey with no plastering, (ii) L/350 for interstorey with plastering below, (iii) L/200 for attic floors or roof purlins and rafters, (iv) L/150 for roof batten and sheathing; and (v) L/400 for roof valleys; (d) BS 5268[12] has recommended a limit of 0.003L subject to a maximum deflection of 14mm; and (e) Percival[29] has recommended: (i) L/240 for floors; and (ii) L/180 for roof and ceiling.

A deflection limit of 1/125th of the simply supported span is recommended for bamboo structures taking into account the following considerations: (a) Unlike a stress there is no stage[26] at which deflection leads to failure of the deflecting member, although there is a stage at which deflection would become visually unacceptable to the majority of people or lead to distortion, cracking or failure of elements such as ceiling or partition under a beam or a waterproof membrane supported by a beam; (b) Cambering is not possible in the case of bamboo, and dead load deflection is very small; (c) Loading is not long term as the structure itself is temporary so creep deflection is not a critical consideration; (d) Deflection limit should not exceed the elastic limit; (e) Ratio of ultimate load to load at deflection limit should not be less than 2.25; (f) span is usually less than 3.0m; (g) Being a temporary structure aesthetic considerations are not important; (h) Damage to adjacent elements like ceilings, partitions or waterproofing elements does not arise; (i) Maximum deflection is likely to occur for short periods as in falsework rather than formwork (where bamboo is not used in flexure); (j) Secondary stresses are unlikely at joints due to excessive distortion or rotation, as joints in bamboo structures are not stiff; and (k) Bamboo temporary structures are usually skeletal structures with no attached infill panels.

In flexural tests, failure occurred with a loud noise followed by longitudinal splitting near the point of loading at mid-span. The separation of fibres occurred just above the neutral axis and even at this stage bamboo was able to carry some residual load. This indicates that bamboo gives adequate warning against failure and also explains why it is recommended[24] for earthquake prone regions.

4.3 Design Compressive (crushing) Stress

Ultimate crushing stress of a specimen was calculated from its ultimate load and minimum sectional area of the bamboo near the failure zone.

Data reduction was carried out similar to that of 4.2 above, and it consisted of application of the specific gravity correction (specific gravity - 0.52 to 0.81), moisture content correction (moisture content - 28% to 115%), and standard statistical technique to obtain design stress at 5% exclusion limit. Values of statistical factor and factor of safety used in compliance with BS 5628[12] and CP112[25] are shown in Table 1. Recommended design crushing stress at a moisture content of 30% is shown in Table 1. Ultimate crushing stress (29.33 N/mm^2) compared well with those reported by Siopongco et al[5] (30.2-55.7) and Jayantha Manel[14] (20.2-43.8). External diameter of the test specimens varied from 60.8 to 99.1mm, while thickness varied from 5.1 to 14.0mm. Variation of slenderness ratio was small (9.36 to 13.32) among the specimens and was found to be insufficient to change the behaviour from crushing to buckling. Coefficient of variation of test results (see Table 1) was within 20% and, hence, satisfactory.

Failure observed was by longitudinal splitting across the node followed by shear failure in the transverse direction clear of the node.

4.4 Design Tensile Stress

Ultimate tensile stress of a specimen was calculated from its ultimate load and sectional area of the narrow stem of the specimen.

Data reduction was carried out similar to that of 4.2 above, and it consisted of application of the specific gravity correction (specific gravity - 0.50 to 0.65), moisture content correction (moisture content - 19.0% to 118.0%), and standard statistical technique to obtain design stress at 5% exclusion limit. Values of statistical factor and factor of safety[12,25] used are shown in Table 1. Recommended design tensile stress at a moisture content of 30% is shown in Table 1, and compared well with those reported by Siopongco et al[5] (29.42) and Janssen[24,27] (20). Wall thickness of the bamboo in the specimens varied from 4.5 to 15.3 mm. coefficient of variation of test results (see Table 1) was within 20% and, hence, satisfactory.

Failure observed was a combination of transverse shear failure[27] and fracture failure of the node accompanied by a loud splitting sound.

4.5 Design Buckling Stress

Ultimate buckling stress of a specimen was calculated from its ultimate load and minimum sectional area of the bamboo near the failure zone.

Buckling stress of an axially loaded specimen is a function of the geometry of the specimen and end conditions. Thus, there does not exist a constant buckling stress but it varies with the slenderness ratio. This meant that standard statistical techniques cannot be applied, as for other design stresses. The common strategy adopted by previous timber researchers[28,25,12] is to evolve a relation between design buckling stress and slenderness ratio by altering the eccentricity coefficient of the Perry-Robertson formula in order to give adequate factor of safety to measured values of ultimate buckling stress. The suitability of CP112[25] and BS 5268[12] approaches were considered in this study. BS 5950[31] approach was not considered as the most favourable formula, which was for structural hollow sections, coincided with that of CP112[12] and a bamboo closely resembles a structural hollow section.

Data reduction carried out consisted of application of the specific gravity correction (specific gravity - 0.52 to 0.80) and moisture content correction (moisture content - 27% to 188%) in a manner similar to that in 4.2 above. Experimental results are shown in Figure 1 by the shaded region. Predicted design values of compressive (buckling) stress by CP112[25] and BS 5268[12] are also shown in Figure 1.

Slenderness ratio of 1.5m long specimens varied from 44.16 to 85.30, 0.9m long specimens varied from 26.28 to 44.28, and 0.6m long specimens varied from 17.52 to 28.44 to give an overall variation between 17.52 and 85.3. These values of slenderness ratio were considered to cover the practical range of slenderness ratios in exposed bamboo structures.

There was no significant correlation between the parameter, node spacing/diameter (3.09 to 6.05), and ultimate buckling stress. External diameter and thickness of test specimens varied from 66.0 to 99.1 mm, and 6.0 to 26.5mm respectively. Radius of gyration varied from 17.58 to 34.25mm.

Table 1 - Recommended Design Stresses (Values)

Property	Corrected mean stress (value) (N/mm²)	Standard deviation (N/mm²)	Coefficient of variation (%)	Statistical factor k	Factor of Safety F	Design stress (value) (N/mm²)
Flexural stress	53.88	9.61	18.00	1.645	2.25	16.70
Mean Modulus of elasticity	18.57×10^3	----	----	----	1.00	18.57×10^3
Minimum Modulus of elasticity	18.57×10^3	3.55×10^3	19.12	1.645	1.00	12.73×10^3
Compressive (crushing) stress	29.33	4.90	16.71	1.645	1.40	15.19
Tensile stress	89.91	17.53	19.50	1.645	2.25	27.14

Table 2 - Modification Factors and Design Compressive (Buckling) Stresses for Bamboo

Slenderness ratio	CP 112*		BS 5268	
	Modification factor compressive stress	Design compressive (buckling) stress for Bamboo (N/mm²)	Modification factor for compressive stress	Design compressive (buckling) stress for Bamboo (N/mm²)
0	1.000	15.19	1.000	15.19
5	0.999	15.17	0.975	14.82
10	0.995	15.11	0.952	14.46
20	0.979	14.87	0.903	13.72
30	0.953	14.48	0.852	12.94
40	0.917	13.92	0.794	12.06
50	0.870	13.21	0.728	11.06
60	0.812	12.34	0.655	9.95
70	0.744	11.31	0.580	8.81
80	0.666	10.12	0.507	7.69
90	0.578	8.77	0.440	6.68
100	0.480	7.29	0.381	5.79

* Values recommended for Bamboo compression members

Modification factors and design compressive (buckling) stresses in Table 2 (based on CP112 theory, design compressive (crushing) stress of bamboo (15.19 N/mm^2) and minimum modulus of elasticity of bamboo (12730 N/mm^2) are recommended for design of bamboo compression members for the following reasons: (a) CP 112 theory specifies enhanced values for design compressive stress than BS 5268 theory; (b) CP112 values give adequate factor of safety against failure; and (c) Eccentricity coefficient (=0.002 L/r) used in CP112 theory is the same as that used for steel members in the form of structural hollow sections in BS 5950[31] since hollow closed sections (which resemble bamboos) behave better in compression than other forms of members such as 1-sections, angles, channels or rectangular sections.

Observed failure patterns were: (a) longitudinal splitting; (b) longitudinal splitting and shear failure in the transverse direction; and (c) shear failure in the transverse direction. In general, short culms displayed type (a) failure while long culms displayed type (c) failure.

5.0 Conclusions

The following conclusions are made from this study: (a) Design recommendations for bamboo in flexure, crushing (compression without buckling), and tension as well as values for modulus of elasticity were evaluated and shown in Table 1; (b) Modification factors for bamboo elements under buckling are developed and shown in Table 2 for use in a manner similar to those of CP 112[25] and BS 5268[12]; (c) All failure mechanisms demonstrate the weakness of bamboo in shear; (d) Deflection limit of 1/125th of the simply supported span was found to be satisfactory for bamboo under flexure in exposed temporary structures; and (e) Node spacing/diameter ratio was not found to affect the key mechanical properties of bamboo.

6.0 References

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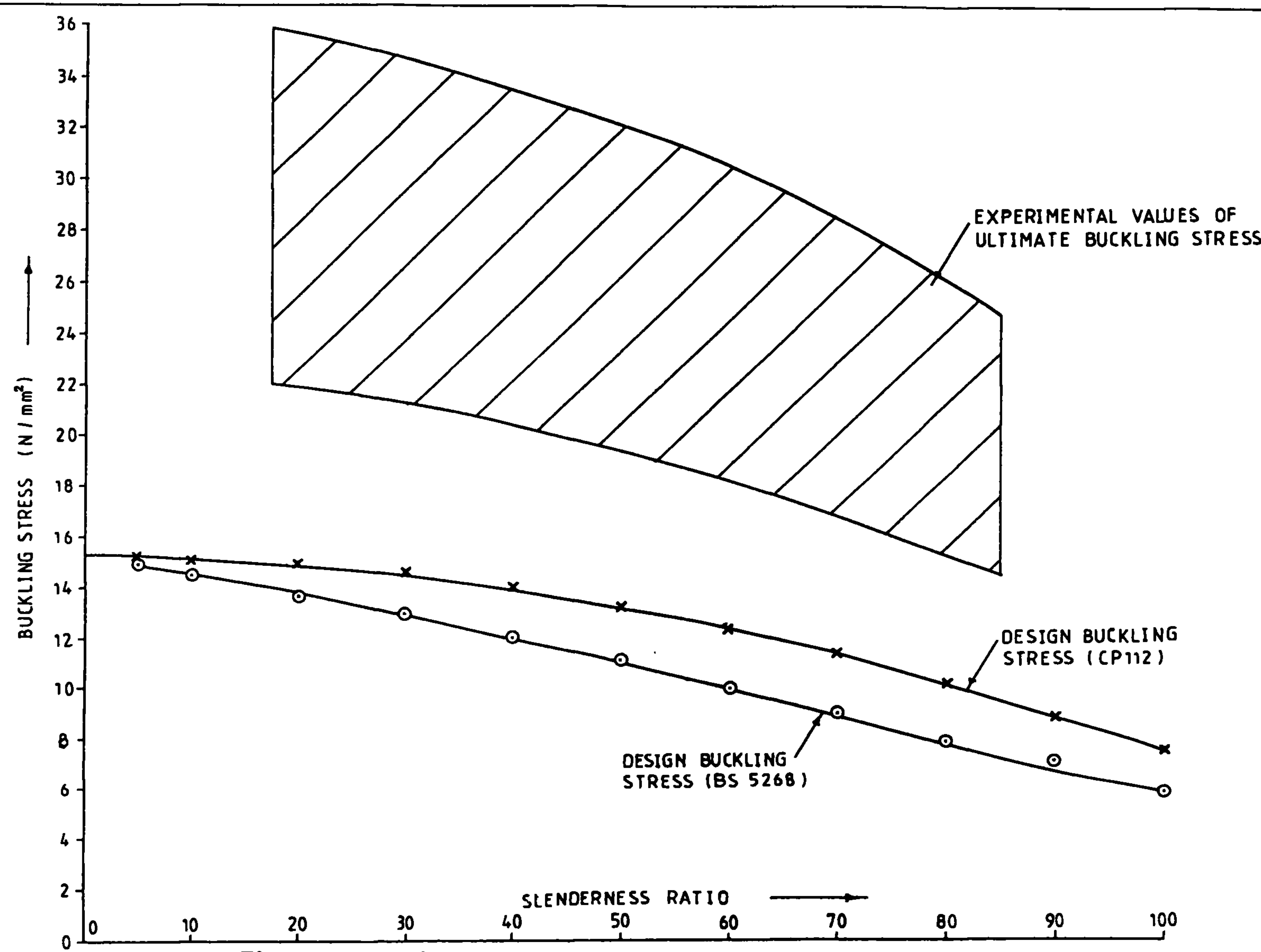

Figure 1 - Variation of Buckling Stress with Slenderness Ratio

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