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Design of space truss structures

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Abstract. Space truss design usually involves two main assumptions: that truss members are pin-ended, and compression members possess brittle post-buckling characteristics. The validity of these assumptions in the design of a new group of space trusses with continuous chords and eccentric joints is questionable. With chord member continuity and the consequent improvement in compression member behaviour, current design practice might be too conservative. In this paper, it is shown that substantial improvements in overall truss strength have resulted when the true member end conditions are considered, thus indicating potential savings in truss weight with considerable magnitudes.

Key words: space trusses; jointing systems; design.

1. Introduction

Since the beginning of their commercial use half a century ago, space trusses have been increasingly popular, especially in large open areas with few or no intermediate supports. Over the years, they have become known for their pleasing appearance, light weight, easy fabrication and rapid erection. Hundreds of successful space truss applications now exist all over the world covering stadiums, public halls, exhibition centres, aeroplane hangers and many other buildings.

For decades, space truss design has been a simple and straightforward operation that requires only a standard linear finite element analysis, and based on the results of this analysis, truss members are sized to remain linear elastic without yielding or buckling until at least the factored load level.

However, several recent research works (Schmidt, *et al.* 1976, Smith 1984, Hanaor 1985, Tada, *et al.* 1993, El-Sheikh 1995) have suggested that linear analyses are not appropriate due to several factors which include the following:

1) The brittle post-buckling behaviour of truss compression members and the scatter found in their buckling loads make it difficult to predict truss strength especially when member buckling is the most likely trigger for failure (Schmidt, *et al.* 1976, Smith 1984, Hanaor 1985).

2) The change in joint coordinates that takes place while loading, alters the distribution, and development rate, of internal member forces. This may lead sometimes to the first cases of member yielding or buckling occurring before the load level predicted by simple linear analyses (El-Sheikh, *et al.* 1993).

3) The rate of force development in compression members has been found to accelerate upon the yielding of a few tension members (Schmidt, *et al.* 1982, El-Sheikh, *et al.* 1993).

4) Space trusses have been proven to be highly sensitive to member geometric imperfections,

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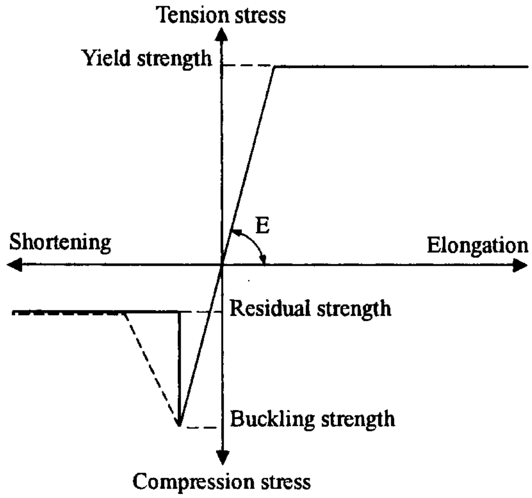


Fig. 1 Idealised truss member behaviour in tension and compression.

and particularly lack of fit, see Hanaor (1985), Tada, *et al.* (1993) and El-Sheikh (1995). Only non-linear analyses could accurately trace truss performance in cases that involve member imperfections.

Alternatively, it has been suggested (Hanaor 1985) that the design should be based on non-linear analyses that involve two primary assumptions: (a) that truss members meet at pin joints, and (b) truss member behaviour in tension and compression is as shown in Fig.1. In this figure, it is shown that while tension members have a long ductile behaviour, compression members are brittle, with a sudden or a gradual loss of strength down to a low residual strength level.

The above two assumptions have been justified by a number of reasons:

(1) Assuming pure pin joints greatly simplifies, and speeds up, the design process.

(2) Most available space truss systems consist of short members prepared with member end fittings and joined together using node connectors in a fashion that leads to low flexural stiffness at member ends (Hanaor 1995a).

(3) Ignoring the partial end fixity of truss members can add a good margin of safety against any unforeseen imperfections.

(4) The jointing systems adopted by different space trusses offer significantly different degrees of member end fixity (Hanaor 1995b,c). It is therefore difficult to choose a certain value or set up a formula that can be used universally to predict the level of member end fixity.

(5) As space trusses deform under load, their joints rotate, leading in effect to a reduced member end fixity.

However, there are cases in which some of the reasons given above become obsolete. Examples of these cases include the following:

(1) A number of space truss systems with continuous chord members and eccentric joints have recently been developed to address the high cost disadvantage of space trusses. Examples of these systems include the Harley and Catrus systems (see Codd 1984 and El-Sheikh 1996). The member continuity and joint eccentricity of these systems provide a high level of member end fixity and a long ductile behaviour, ignoring which would certainly lead to a highly conservative design. These systems have also been found more tolerant to cases of member lack of

fit due to the different nature of their jointing systems.

(2) Several techniques are now available to prevent compression member buckling including the use of force limiting devices (Schmidt, *et al.* 1979, Parke 1993), the overdesign of compression members (Hanaor, *et al.* 1989) and the prestressing of a selection of truss members (Hanaor, *et al.* 1989). With these techniques, space trusses become more dependent on the ductile characteristics of their tension members, and consequently, considerable improvements to truss ductility and strength usually occur.

In space truss systems that employ any of these techniques, significant material savings can be achieved by considering the enhanced properties of the compression members, and by allowing some tension member yielding to take place.

(3) Space trusses may act compositely with top concrete slabs (Kuleib 1989, McConnel, *et al.* 1991, El-Sheikh, *et al.* 1993). In these systems, the concrete slab is usually much stiffer than the top chord members, and therefore carries most of the top chord compression forces. Even, if the development rate of these forces accelerates due to cases of bottom member yielding, the concrete slab remains able to survive due to its inherent high in-plane strength.

Additionally, in composite trusses, the concrete slab is rigidly connected to the top members and the top joints, and therefore offers significant member end fixity to both the top and the diagonal members. Also, composite space trusses have been found much less sensitive to member geometric imperfections than their non-composite equivalents (El-Sheikh 1995).

This paper is devoted to assessing the validity of the two main assumptions adopted in space truss design, namely; the pin joints and the compression member brittle behaviour. Several truss members with different end jointing systems have been tested experimentally in compression. The jointing systems included are a selection of the most commonly used in practice (including that of space trusses with continuous chords and eccentric joints). The aim of this part of the work is to determine the effect of different jointing systems on member behaviour in compression.

It should be noted that an earlier research work that involved testing in tension several truss members with different member ends, was conducted by Schmidt, *et al.* (1986). In this work, it was found that tension members generally experienced a long stage of ductile behaviour; a finding that has been adopted in the numerical modelling of truss tension members in the present work.

This paper also introduces two numerical studies on the effect of compression member behaviour and member end fixity on overall truss behaviour. The studies are parametric, and cover wide ranges of truss aspect ratios, boundary conditions and member behaviour patterns. The composite action between the space truss and a top concrete slab is also included as a parameter.

As a result of this work, conclusions are drawn on efficient design practices for space trusses which take into account the economy, safety and reliability aspects of design. Distinction is clearly made between space truss systems with concentric short members and node connectors, and those with continuous chord members and eccentric joints.

2. Experimental programme

The experimental programme of this work was designed to assess the effect of different member end conditions and jointing systems on the behaviour of truss compression members. The behaviour patterns obtained herein were then adopted in full truss analyses to demonstrate the likely effects of these two factors on overall performance.

2.1. Test specimens

The twenty two buckling tests that were carried out in this programme were divided into two main test series:

1) Series 1 involved 12 Rectangular Hollow Section (RHS) members loaded by axial compression forces until, and beyond, buckling. The twelve specimens included were 6 RHS 20×20×2.0 and 6 RHS 25×25×3.0, with each group containing 3 pairs tested with fixed ends, pinned ends and fixed, eccentric ends, respectively (see Fig. 2). In the third case, the eccentricity adopted was equal to half the width of the test members (in order to represent the jointing system of space trusses with continuous chords and eccentric joints). All specimens were 800 mm long and made of steel of grade S355N.

   The purpose of this series was to study the behaviour of truss chord members in systems with continuous chords and eccentric joints. The fixed-ended and the pin-ended members included in this group were used as control specimens to enable the assessment of the effect of both continuity and eccentricity on member behaviour.

2) Series 2 included five pairs of specimens with the ends shown in Fig. 3. These ends were typical of five distinctive jointing methods used by the following commercial space truss systems (Hanaor 1995c):
   - Joint 1 used by Unibat (France).
   - Joint 2 used by Mai Sky (Mai Sky, USA), Multi-Hinge System (Pearce, USA), CABIR (Centro Acciai, Italy), Tritec (Israel).
   - Joint 3 used by Octatube (Netherlands) and Harley (Australia), Triodetic (BACO, UK).
   - Joint 4 used by Catrus (UK) and Harley (Australia).
   - Joint 5 used by KK-System (Mero, Germany), Uzaykon (Rafid, Saudi Arabia), Züblin (Germany).

The eight members tested with the first four jointing systems were Circular Hollow Section (CHS) 26.9×3.2, with 800 mm length. The two members with the fifth jointing system were CHS 28.58×1.63, and had the same length. All test members were made of grade-S355N steel.

Series 2 was included in this work to study the behaviour of truss (chord and diagonal) members in systems with short members and concentric joints. The members tested were also typical of the diagonal members in systems with continuous chords and eccentric joints, e.g., Catrus and Harley. The five jointing systems chosen are among the most commonly used in practice with space truss structures.

All members were loaded by axial compression forces until buckling occurred and a constant level of residual strength was reached. The members had fixed ends to model the effect of actual truss joints and other neighbouring members in restraining their buckling. Adopting this assumption meant, however, that the possible joint rotations which could reduce the level of member end fixity had been ignored.

2.2. Test procedure

All compression tests were carried out in a 500 kN-capacity Instron 1196 testing machine, under a controlled rate of deformation of 2 mm/min throughout. The tests continued beyond the buckling of the specimens and until a constant residual strength level was reached. Load shortening curves were drawn automatically for every test by the testing machine plotting facility.

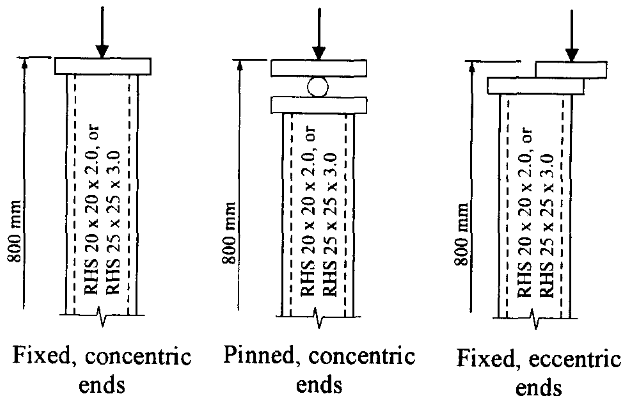


Fig. 2 Different ends of Series 1 members.

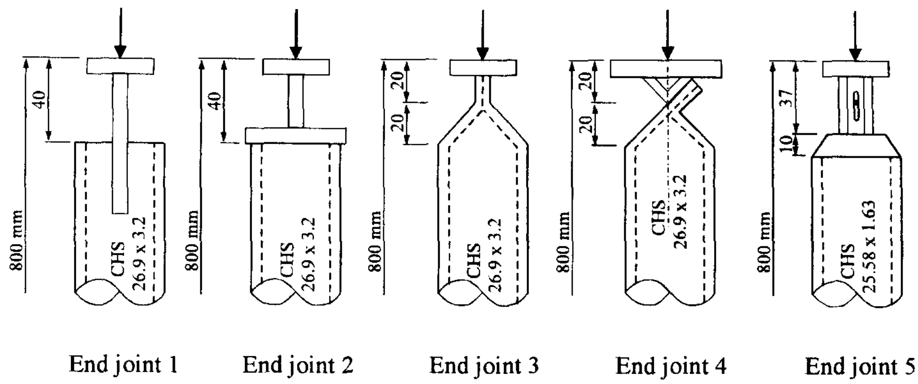


Fig. 3 Different ends of Series 2 members.

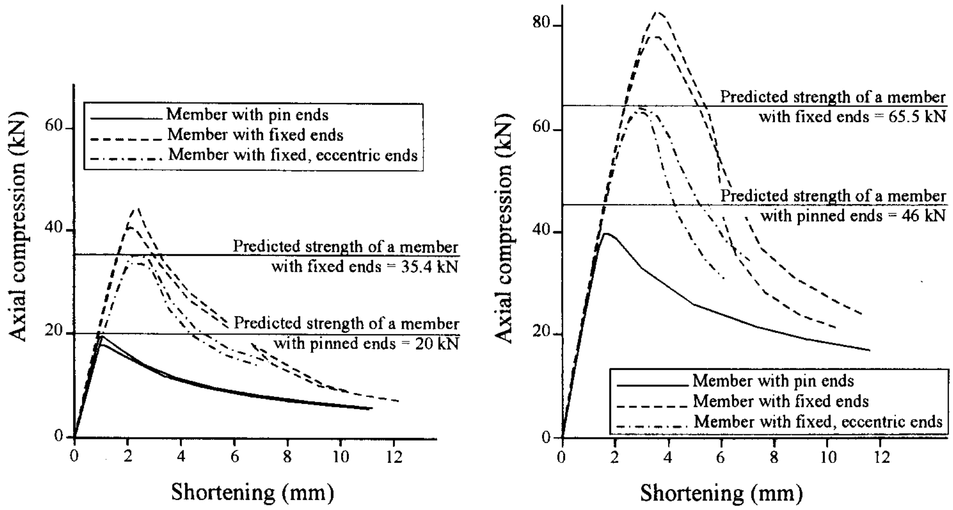
2.3. Test results of Series 1 and discussion

The load shortening relationships obtained for the twelve specimens of Series 1 are shown in Fig. 4. The figure also shows the buckling loads predicted analytically according to the British Standard Specification, BS 5950 (1985).

Fig. 4 demonstrates that in all cases studied, the strength of members with fixed and eccentric supports was between those of members with pinned and fixed, concentric supports. With the eccentricity considered (which was close to what would practically be expected in systems with continuous and eccentric chords), members with fixed and eccentric supports achieved increases in strength of 59-70% above similar members with pin ends. On the other hand, the effect of eccentricity in enhancing the members' ductility was evident, especially with RHS $25 \times 25 \times 3.0$ members. Some scatter was observed in the peak load values of the members tested, and ranged between 1% and 9%.

The results presented also demonstrate that, in all cases studied, the experimental buckling strengths for members with fixed and eccentric ends were much closer to the theoretical predictions for fixed-ended cases, than to the predictions for pin-ended cases. This observation has been used effectively in the numerical studies presented below.

Furthermore, it can be seen from Fig. 4 that the member end conditions did not have a not-



(a) Results for RHS 20x20x2.0 members (b) Results for RHS 25x25x3.0 members

Fig. 4 Experimental behaviour of Series 1 test members under axial compression.

able effect on its initial stiffness. This observation is compatible with the general point made earlier by Madi (1984) that the stiffness of compression members did not depend on their end conditions.

2.4. Test results of Series 2 and discussion

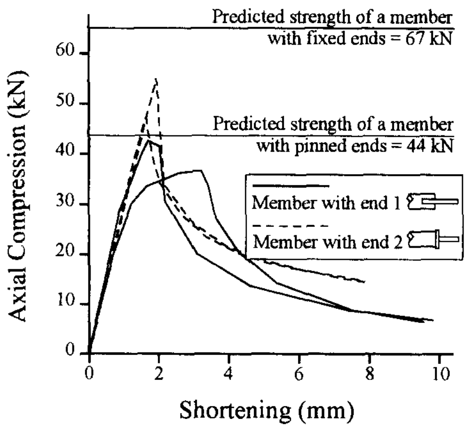
The experimental behaviour of Series 2 specimens with five different jointing systems is presented in Fig. 5. All specimens experienced linear behaviour until the buckling load level, beyond which a sudden loss of strength occurred down to a low residual level between 15% and 32% of the peak load for all specimens. Fig. 5 also shows that while there was some considerable scatter in the peak loads recorded (9-16%). these loads were in most cases between the predicted values for pin-ended and fixed-ended members.

The worst performance was associated with members prepared with end joint 1 where the buckling strength was below the predicted value for a pin-ended member by 3-16%. This indicated that this style of member ends had introduced considerable instability under compression. With the other jointing systems, the behaviour notably improved with the members exceeding the predicted strength for the pin-ended case by 6-25%, 16-28%, 15-35%, 3-14% for end joints 2 to 5, respectively.

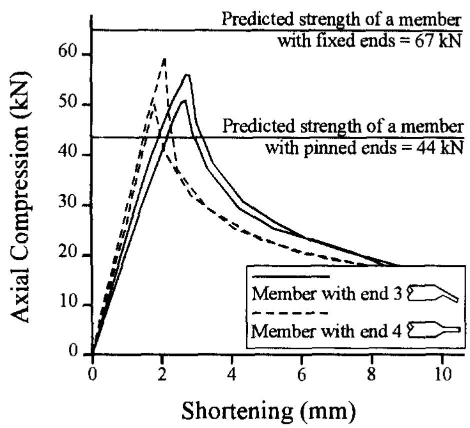
In overall, it seems that assuming member buckling to occur at the theoretical peak loads of pin-ended members is, in most cases, reasonable and safe in space trusses with short chord members and node connectors, and with the jointing systems considered. The main points that support this conclusion are the considerable scatter in peak loads, that these loads are generally close to the pin-ended member strength, and the possible joint rotation of truss joints (which have not been considered in this test programme).

2.5. Overall comments on experimental results

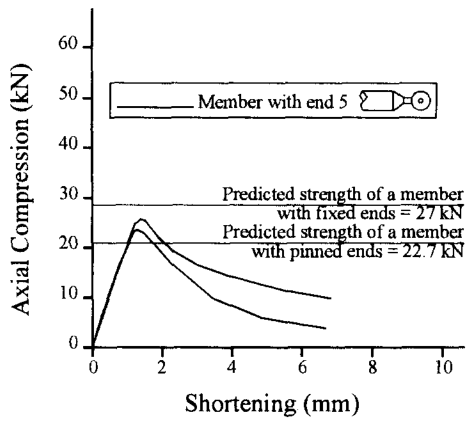
The experimental results presented above illustrate the following points:



(a) Results of members with end joints 1 and 2



(b) Results of members with end joints 3 and 4



(c) Results of members with end joint 5

Fig. 5 Experimental behaviour of Series 2 test members under axial compression.

(1) The Series 1 members with fixed and eccentric ends modelled the chord members in space trusses with continuous chords and eccentric joints. With their combination of end fixity and eccentricity, they achieved buckling strengths close to those predicted theoretically for fixed-ended members. A tangible improvement in their ductility was also evident.

These findings suggest that for space trusses with continuous chords and eccentric joints, it may be safe to assume that their chord members would buckle at, or slightly below, the fixed-ended level. Some ductility could also be introduced in the numerical idealisation of the behaviour of compression chord members. The effect of these points on truss design is assessed in the numerical studies presented below.

(2) Testing Series 2 members with five different end joints resulted in strengths close to the theoretically predicted values for pin-ended members. Most members experienced a scatter in peak load values and a sudden loss of strength triggered by buckling. These findings indicate that the current design practice based on members meeting at pin joints and having a brittle post-buckling behaviour, is adequate for space trusses with short members and node connectors. Ad-

ditionally, the diagonal members of space trusses with continuous chords and eccentric joints should be treated similarly.

As a consequence of these two points, the numerical studies presented below are primarily focused on space trusses with continuous chords and eccentric joints as it has been shown that the current design practice is adequate for systems with short and concentric members.

3. Analytical programme

The analytical programme included in this work has two explicit aims; to study the effect of (a) compression member behaviour, and (b) member end fixity, on overall truss performance.

In order to fulfil these aims, two parametric studies were conducted:

(1) In the first study, twelve space trusses were tested analytically under uniformly distributed loads, increasing to failure. Each truss was tested four times with four different behaviour patterns adopted for its compression chord members as shown in Fig. 6. This figure presents an approximate idealisation for the behaviour patterns obtained experimentally for Series 1 specimens, Fig. 4. On the other hand, all compression diagonal members were assumed to follow behaviour pattern 2 of Fig. 6. This assumption is compatible with the results of the experimental programme presented above.

Tension yielding was assumed to start at a stress of 355 N/mm^2, and a pure plastic behaviour dominated thereafter. All truss joints were modelled as pin joints in line with the usual design practice.

(2) In the second study, each of the twelve space trusses was studied twice; with the chord members modelled as pure truss elements and beam elements, respectively. The diagonal members were modelled as pure truss elements in all cases according to the findings of the present experimental study. The compression member behaviour 2 illustrated in Fig. 6 was used throughout. Also, a ductile tension member behaviour like that described in (1) above, was considered once yielding occurred.

3.1. Design of space trusses

Twelve space trusses were designed in the present work. They included:

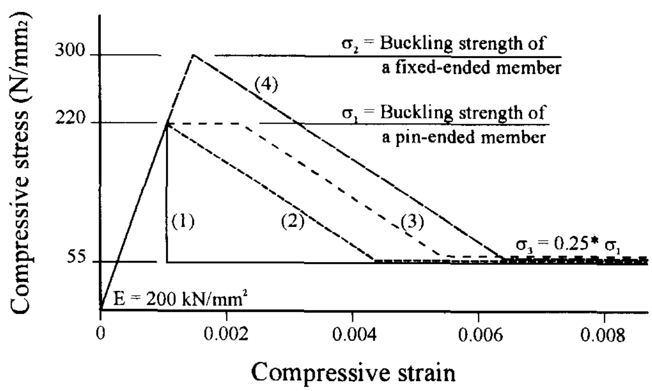


Fig. 6 Compression member behaviour patterns considered in the unmerical analyses.

1) Trusses with aspect ratios of 1:1, 1½:1 and 2:1, with 12×12 bays, 18×12 bays and 24×12 bays, respectively. These trusses had overall dimensions of 18m×18m, 27m×18m and 36m×18m, all with a 1m depth. see for example Fig. 7.

2) Six trusses with corner supports and six with edge supports.

3) Six trusses with top composite concrete slabs and six without (See Fig. 8 and Table 1).

The concrete slabs used in the composite trusses were of a light weight, 80 mm thick and of grade 25. This slab thickness was sufficient to carry the uniformly distributed load applied while being supported in two directions on the top chord members. The thickness was also adequate to resist the in-plane compression forces transmitted to the slabs at the top chord joints.

All trusses were designed under a uniformly distributed dead load of 1.0 kN/m^2 and live load of 3.0 kN/m^2, giving a total factored load of 6.2 kN/m^2. Truss dimensions and loading were chosen to model space trusses with practical and realistic properties.

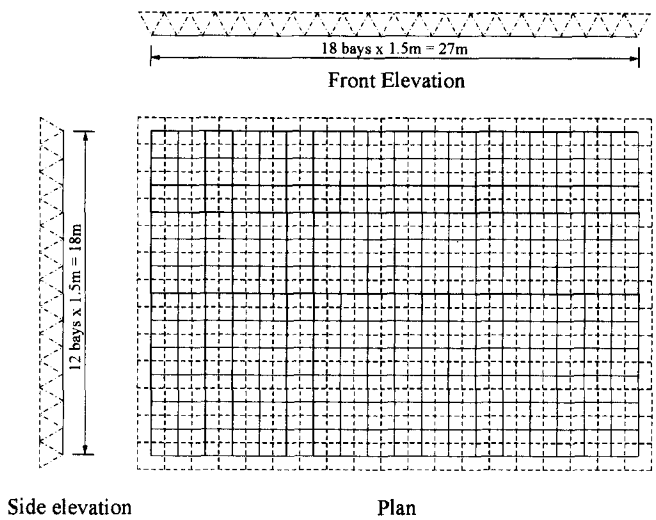


Fig. 7 Example layout of a 1½1 space truss.

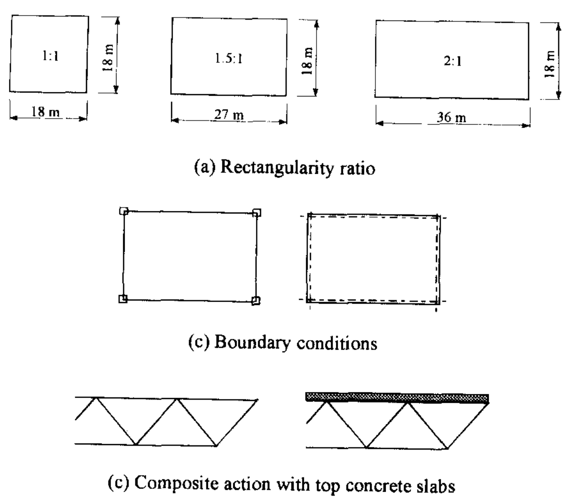


Fig. 8 Parameters considered in the numerical studies.

Table 1 Member szes

Truss	Member sizes					
	Top members		Bottom members		Diagonal members	
	Heavy*	Light	Heavy*	Light	Heavy⁺	Light
T11crn	RHS 120 × 80 × 10.0	RHS 100 × 50 × 3.2	RHS 100 × 50 × 3.2	RHS 60 × 40 × 2.5	CHS 193.7 × 6.3	CHS 139.7 × 5.0
T11cry	RHS 20 × 20 × 2.0	RHS 20 × 20 × 2.0	RHS 60 × 40 × 5.0	RHS 60 × 40 × 2.5	CHS 193.7 × 6.3	CHS 139.7 × 5.0
T11edn	RHS 80 × 40 × 5.0	RHS 20 × 20 × 2.5	RHS 25 × 25 × 2.5	RHS 20 × 20 × 2.0	CHS 33.7 × 3.2	CHS 33.7 × 3.2
T11edy	RHS 20 × 20 × 2.0	RHS 20 × 20 × 2.0	RHS 25 × 25 × 2.5	RHS 20 × 20 × 2.0	CHS 33.7 × 3.2	CHS 33.7 × 3.2
T15crn	RHS 300 × 200 × 10.0	RHS 150 × 100 × 6.3	RHS 90 × 50 × 8.0	RHS 90 × 50 × 5.0	CHS 193.7 × 10.0	CHS 193.7 × 8.0
T15cry	RHS 20 × 20 × 2.0	RHS 20 × 20 × 2.0	RHS 90 × 50 × 8.0	RHS 90 × 50 × 3.6	CHS 193.7 × 10.0	CHS 193.7 × 8.0
T15edn	RHS 100 × 60 × 6.3	RHS 20 × 20 × 2.0	RHS 40 × 40 × 2.5	RHS 20 × 20 × 2.0	CHS 42.4 × 2.6	CHS 42.4 × 2.6
T15edy	RHS 20 × 20 × 2.0	RHS 20 × 20 × 2.0	RHS 40 × 40 × 2.5	RHS 20 × 20 × 2.0	CHS 42.4 × 2.6	CHS 42.4 × 2.6
T21crn	RHS 300 × 200 × 12.5	RHS 160 × 80 × 10.0	RHS 90 × 50 × 8.0	RHS 90 × 50 × 5.0	CHS 193.7 × 16.0	CHS 193.7 × 10.0
T21cry	RHS 20 × 20 × 2.0	RHS 20 × 20 × 2.0	RHS 160 × 80 × 8.0	RHS 100 × 60 × 6.3	CHS 193.7 × 16.0	CHS 193.7 × 10.0
T21edn	RHS 90 × 50 × 8.0	RHS 20 × 20 × 2.0	RHS 50 × 30 × 4.0	RHS 50 × 25 × 2.5	CHS 42.4 × 3.2	CHS 42.4 × 3.2
T21edy	RHS 20 × 20 × 2.0	RHS 20 × 20 × 2.0	RHS 50 × 30 × 3.2	RHS 50 × 25 × 2.5	CHS 42.4 × 3.2	CHS 42.4 × 3.2

Notes
*Heavy top and bottom members are along the edges of corner-supported trusses and in the middle regions of edge-supported trusses.
⁺Heavy diagonal members are those close to the truss supports.

Simple linear analyses, based on the finite element method, were carried out to determine the internal forces in truss members under the total factored load. And according to these forces, truss members were designed assuming steel grade S355N throughout. Six different member sizes were chosen for every truss, the heaviest of which were at truss edges in the corner-supported cases, and in truss central regions in the edge-supported cases. The diagonal members attached to the corner supports were also heavy. The member sizes used in the designed trusses are presented in Table 1.

3.2. Method of analysis

The space trusses included in this analytical programme were analysed using ABAQUS, a non-linear finite element software package well-known for its accuracy and reliability. The analyses considered both geometric non-linearities (due to change of joint co-ordinates) and material non-linearities (due to buckling, yielding, cracking and crushing). Truss members were modelled either as simple two-noded truss elements with no end flexural stiffness and 3DoF per node, u, v, w, or as two-noded beam elements with 6DoF per node, u, v, w, θ_x, θ_y and θ_z.

The top slabs of composite trusses were modelled using four-noded plate elements with six degrees of freedom per node, u, v, w, θ_x, θ_y and θ_z, hence providing flexural stiffness at top truss joints. The material non-linearities (due to cracking and crushing) of the concrete slabs were considered by employing the stress-strain relationships given by Vecchio (1989) for concrete in tension and compression.

3.3. Results of first analytical study

In the first analytical study, the twelve space trusses designed in this work were analysed while considering four different behaviour patterns for compression chord members, Fig. 6. Due to the wide spectrum of parameters covered in this study, it has not been practical to present all the behaviour comparisons obtained, and therefore, only a selected group is included to assist the discussion in this section.

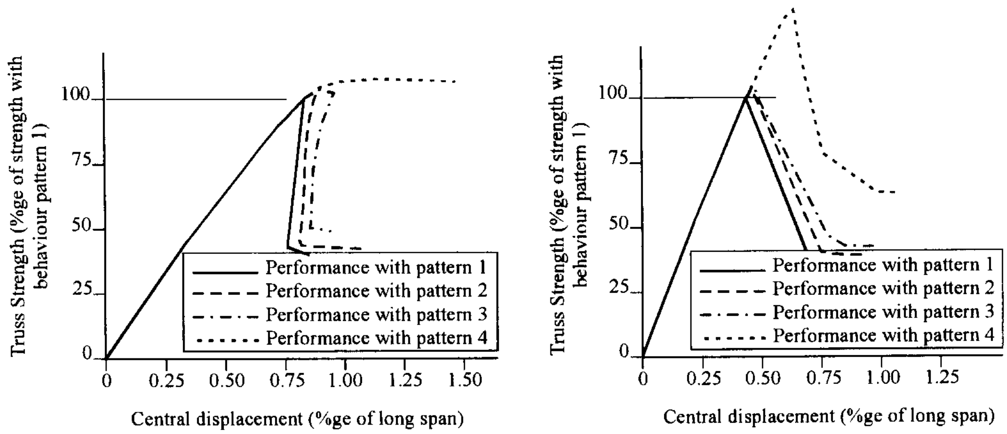
The overall performance of corner-supported trusses T11crn and T21crn, with the compression members modelled with four different behaviour patterns is shown in Fig. 9. It is clear that the behaviour of the two trusses improved when their compression members had a more gradual loss of strength upon buckling and/or a higher buckling stress. The figures show, however, that the trusses responded in two different ways to the improvements in member behaviour. While T11crn became more ductile, T21crn gained a higher strength. This difference in truss response was due to the tension members being slightly undersized in T11crn and oversized in T21crn. Consequently, in T11crn, damage started due to tension member yielding leading to some non-linearity (and hence, the improved ductility). This caused the rate of force development in the compression members to accelerate, resulting eventually in the rapid buckling of a number of compression members, and the overall truss collapse.

When pattern 4 was adopted in the analysis of T11crn, the compression members became stronger, and that allowed more tension members to yield, leading to a more ductile performance. This improved ductility, however, was not associated with a significant strength increase as the tension member yielding was widespread in this case.

Truss T21crn, on the other hand, had oversized tension members. Therefore, its tension members did not yield, and the truss showed linear behaviour until buckling occurred. And as no yielding was experienced, the rate of force development in the compression members remained constant, and that in turn, led to the significant strength improvements associated with behaviour patterns 2, 3 and 4.

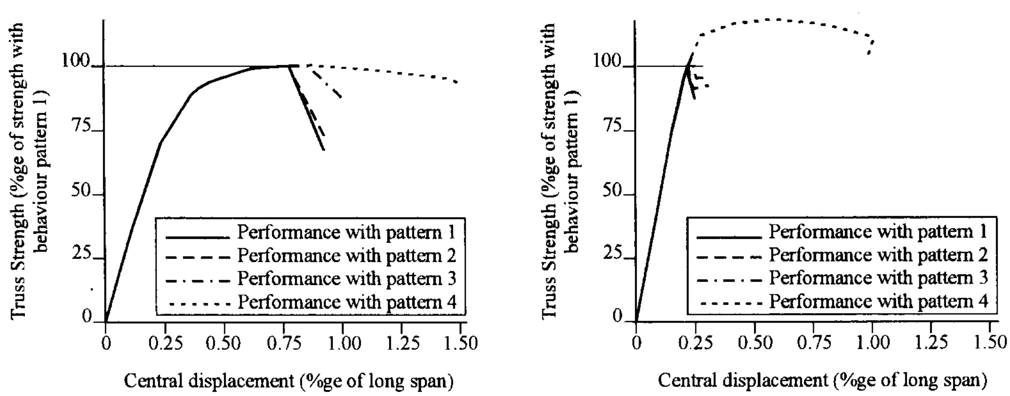
Similar observations to those made above were applicable to the behaviour of two edge-supported trusses, T15edn and T21edn, see Fig. 10. The overall ductile behaviour that was associated with behaviour pattern 4 resulted from the widespread tension yielding of bottom chord members of any critical compression members.

Finally, when composite trusses were tested analytically, it was clear that changing the behaviour of top compression members did not produce any notable alteration in overall performance which was always ductile with a long plastic stage of behaviour. This was due to the large in-plane stiffness and strength of the concrete slab which made the top members largely uncritical to truss integrity.



(a) Truss T11crn (b) Truss T21crn

Fig. 9 Behaviour of trusses T11crn and T21crn with four different compression member behaviour patterns.



(a) Truss T15edn (b) Truss T21edn

Fig. 10 Behaviour of trusses T15edn and T21edn with four different compression member behaviour patterns.

3.4. Results of second analytical study

The aim of this study was to assess the effect of chord member continuity on overall truss response. In that, the effect of continuity on member strength and behaviour was ignored as this was the subject of the first analytical study. Therefore, the global effects of member continuity on truss performance were the sole focus of attention herein.

In this study, the twelve space trusses considered were analysed under increasing loads to failure. Every truss was tested twice; with the chord members modelled as pure truss elements and beam elements, respectively. In all cases, the diagonal members were modelled as truss elements in line with the findings of the experimental study presented above. And in all analyses, whether with truss or beam elements, it was assumed that all compression members followed behaviour pattern 2 shown in Fig. 6. This pattern was chosen for being the most commonly adopted in practice.

As with the first analytical study, not all the results obtained have been presented in this section, and only a selected group is included to assist the discussion.

The load central deflection behaviour of the-corner supported space truss T21crn is shown in Fig. 11. The figure shows that while modelling the chord members as beam elements did not alter the initial stiffness of the truss (as it was primarily dependent on the axial properties of its members, which did not change), significant improvements in strength and ductility resulted. It seems that with continuity (that was modelled herein with the use of beam elements), the truss compression chord acted as a plane frame braced by the diagonals, and loaded at the joints with in-plane forces. Continuity therefore allowed understressed members to restrain the buckling of overstressed members, and that created a better ability to redistribute forces and made trusses more tolerant to individual cases of member loss, see Hanaor (1989). The only situation in which this effect would be invalid is if the truss is designed such that all its compression members have the same factor of safety, and therefore, are likely to buckle simultaneously. In this case, the compression members can not restrain each other's buckling. This case, however, is not practical.

Same observations can be extracted from Fig. 12 depicting the behaviour of edge-supported truss T21edn. With the better ability to distribute forces associated with beam elements, tension member yielding was allowed to spread through the bottom chord, producing a long plastic stage of behaviour. Even when some compression members buckled, the forces they shed were

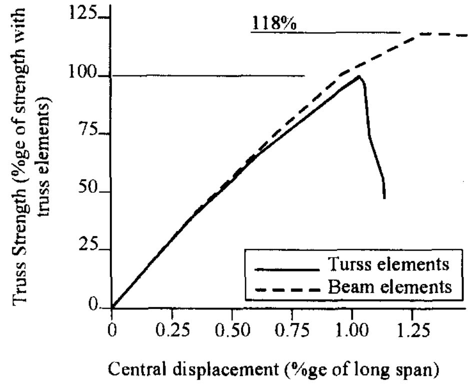


Fig. 11 Behaviour of truss T21crn with the chord members modelled as truss or beam elements.

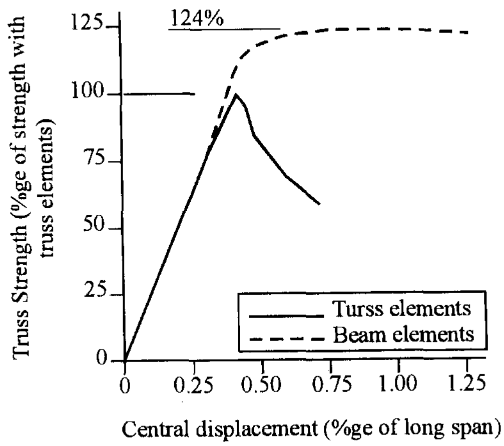


Fig. 12 Behaviour of truss T21edn with the chord members modelled as truss or beam elements.

distributed in a controlled manner to many neighbouring members, and that reduced the likelihood of triggering a progressive collapse.

When the six composite trusses designed in this work were analysed, no significant difference in their overall performance was produced by the use of beam elements. This was due to the inherently large in-plane stiffness and strength of the top concrete slabs which added significant flexural stiffness to truss top joints and reduced the role played by truss top chord members to one secondary importance.

The results obtained also show that modelling the tension bottom members as beam elements had only a minute effect on truss performance. This finding is thought to be reasonable as no loss of strength is associated with member yielding. And it seems, therefore, that the tension members do not benefit from the good force redistribution ability achieved with chord member continuity.

3.5. Overall comments on analytical results

The results presented in the previous two sections reveal a number of important common trends. Most importantly is the benefit in terms of enhanced truss strength and/or ductility, caused by improvements in compression member behaviour and chord member continuity. Although these two factors have been studied separately herein, they are likely to develop simultaneously when chord continuity is guaranteed, e.g., in truss systems with continuous chords and eccentric joints. In this case, the combined improvement in truss strength and ductility is expected to exceed those produced by each factor individually.

The results also indicated that while modelling continuity in the compression chord made a significant difference in the predicted performance of the space truss, little change resulted from considering continuity in the tension chord. This finding is thought to be reasonable as continuity does not alter the tension properties of truss members, and that (unlike the compression members) the tension chord does not benefit from the better ability to redistribute forces associated with continuous chords. Therefore, it is recommended that tension members be modelled as pure truss elements with pin ends, even in space trusses with continuous chord members.

Finally, the work done on composite space trusses showed clearly that as the top chord members, in this case, were largely uncritical to truss integrity, modelling continuity in these members did not have any considerable overall effect. Therefore, it should be acceptable to model the top members of composite trusses as pin-ended truss elements, even in truss systems with continuous chords.

4. Conclusions

The work presented in this paper included two phases; an experimental programme on individual members with different end conditions and jointing systems, and an analytical programme to implement the findings of the first phase in overall truss analyses. From the results of this work, the following conclusions can be drawn:

(1) The current space truss design practice that assumes pin-ended elements and brittle post-buckling member behaviour, is adequate for trusses with short members and concentric node connectors.

(2) In space truss systems with continuous chords and eccentric joints, substantial savings can be achieved if the actual enhanced properties of their compression chord members are considered in the design. In this case, member continuity, an enhanced buckling stress and a degree of post-buckling ductility are the factors that can safely be introduced in modelling the compression chord members. Experiments on individual compression members, are however needed to determine the buckling stress and the ductility extent that can be incorporated in the analysis.

(3) In composite space trusses, the top chord members are no longer critical to truss integrity, and therefore, altering the way they are modelled does not produce any notable effect on truss analysis.

(4) It is recommended, even in space truss systems with continuous chords, that tension chord members be modelled as simple truss elements. Modelling these members as beam elements (to acknowledge their actual continuity) does not produce any notable effect on overall truss performance.

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