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Improving buckling response of the square steel tube by using steel foam

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Abstract. Steel tubes have an efficient shape with large second moment of inertia relative to their light weight. One of the main problems of these members is their low buckling resistance caused from having thin walls. In this study, steel foams with high strength over weight ratio is used to fill the steel tube to beneficially modify the response of steel tubes. The linear eigenvalue and plastic collapse FE analysis is done on steel foam filled tube under pure compression and three point bending simulation. It is shown that steel foam improves the maximum strength and the ability of energy absorption of the steel tubes significantly. Different configurations with different volume of steel foam and composite behavior is investigated. It is demonstrated that there are some optimum configurations with more efficient behavior. If composite action between steel foam and steel increases, the strength of the element will improve, in a way that, the failure mode change from local buckling to yielding.

Keywords: steel foam; steel tube; plate buckling; imperfection; finite element analysis

1. Introduction

Steel tube beams and columns are able to provide significant strength for structures. They have an efficient shape with large second moment of inertia which leads to light elements with high bending strength. Moreover, they can resist loading in multiple directions, and have large torsional strength. One of the drawbacks of tubular cross sections with thin walls is their susceptibility to local buckling. Having thin walls forces the element to buckle locally before the cross section can show its maximum capacity through full yielding. Moreover, this local buckling will cause low ductility in the element response.

One method of increasing the ductility and capacity of tubular elements is filling them with another material. One of the classical materials which is used for this purpose is concrete. There are large numbers of studies on the behavior of concrete-filled columns and beam-columns such as the research done by Furlong (1967), Shakir-Khalil and Mouli (1990), Prion and Boehme (1994), Schneider (1998), Varma *et al*. (2002), Han (2004), Lu *et al*. (2007), Chitawadagi and Narasimhan (2009), Chen *et al*. (2012), Chacon *et al*. (2013) which show that there is a substantial

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increase in the axial strength, moment of inertia and the corresponding peak curvature of the hollow sections when they are filled with concrete. In these researches, the strength and ductility of the concrete filled steel tube, the concrete effects on post yielding ductility of steel tubes and the concrete confinement by steel tubes were investigated.

Although concrete is cheap and easy to use, it is brittle. Therefore, steel foam which may be able to perform with greater ductility at lower weight can be used to enhance the buckling capacity of thin walled structures more efficiently. Szyniszewski *et al*. (2012) investigated the local buckling behavior of steel foam sandwich panels and they found that significant strength improvements were possible for steel foam sandwich panel compared to solid steel. Smith *et al*. (2012), Moradi *et al*. (2012) also proposed some structural application for steel foam and showed that by controlling the density, steel foam can be used to improve the structural behavior.

In this study the potential for using ductile steel foams to improve local buckling resistance of steel tube is evaluated. First, the characteristics of metal foams in compression and tension will be reviewed. Considering that local buckling of the tube walls is essentially a manifestation of plate buckling, a theory of plate buckling with different kinds of boundary conditions will be presented in the next section. That will be followed by finite element modeling of a steel foam filled thin walled square steel tube, which is called a foam filled tube for the rest of the paper. This system, a foam filled tube, previously has been analyzed in one experimental study (Fraunhofer 2004). In the current study the strength of the foam filled tube under bending and axial actions is estimated by eigenvalue and plastic collapse analysis. The effect of different geometries of the steel foam fill on the response of the element is investigated. The effect of the degree of composite action between the foam and tube on strength is also evaluated. Finally there is a discussion of the results of the finite element modeling.

1.1 Steel foam characteristics

Steel foams are a relatively new class of materials with low densities and novel physical, mechanical, thermal, electrical and acoustic properties. They have potential for forming lightweight structures, for energy absorption, and for thermal management (Ashby *et al*. 2000).

In the compressive stress-strain curves for typical steel foams, the response is linear elastic at low stresses followed by a long collapse plateau, terminating in a regime of densification in which the stress rises steeply. Linear elasticity is controlled by cell wall bending and, if the cells are closed, by cell face stretching. In compression the plateau is associated with collapse of the cells by formation of plastic hinges in the cell walls of ligaments. When the cells have almost completely collapsed, intercellular contact occurs, rapidly increasing stress. These properties, particularly the long plateau are important in energy-absorbing application, to which steel foams lend themselves well. In tension, initial linear elasticity is caused by cell wall bending, plus stretching, if the cells are closed. The cell walls rotate towards the tensile axis by plastic bending, giving a yield point followed by a rising stress-strain curve, which ultimately ends in fracture (Gibson and Ashby 1999).

2. Plate buckling

Local buckling of the walls of a thin walled steel tube is actually a manifestation of the buckling of the plates forming the walls of the tube. The addition of metal foam within the steel tube provides a support for the plate or, in another interpretation, thickens the plate. This section of the study reviews plate buckling theory with different types of boundary conditions. An important feature of plate buckling is that the plate can continue to resist increasing axial force after reaching the critical load, and plates can exhibit substantial post-buckling reserve strength (Chajes 1974).

2.1 Uniaxially compressed plate

The critical load of plates, like columns, depends on the boundary condition of the plates. Moreover, a plate's buckling load and mode shape depends on the aspect ratio of the plate. Generally, the critical load of the plate can be calculated by

$$N_x = \frac{k\pi^2 Eh^3}{12(1-\mu^2)b^2} \tag{1}$$

in which N_x is the critical load per unit length, E is the plate elastic modulus, h is the plate thickness, b is the plate width, μ is Poisson's ratio and k is the buckling stress coefficient for a uniaxially compressed plate. The value of k is related to the boundary conditions and aspect ratio of the plate (Chajes 1974).

For the tube walls, if the ratio of b/t is large, it can be assumed that the tube walls act as simply supported plates so that Eq. (1) can be used to calculate the critical load for local buckling of the empty tubes. This analogy can be extended by treating the walls of a tube filled with foam as plates supported by elastic foundations.

2.2 Plate uniformly compressed in one direction on an elastic foundation

The behavior of the walls of a metal foam filled steel tube is similar to the behavior of plate on an elastic foundation. The buckling load of a plate that is rigidly attached to its elastic foundation with integer or greater than 4 aspect ratio is

$$N_x = \frac{2(1+\sqrt{1+\gamma})\pi^2 Eh^3}{12(1-\mu^2)b^2} \tag{2}$$

in which γ is equal to

$$\gamma = \frac{\hat{k}12(1-\mu^2)}{Eh^3}\left(\frac{b}{\pi}\right)^4 \tag{3}$$

and k is the foundation stiffness per unit area (Seide(1958)). Fig. 1 shows the parameters of the plate on elastic foundation problem. If the γ value is substituted by the equivalent stiffness of the metal foam, Eq. (2) can be used to approximate the local buckling capacity of a metal foam-filled steel tube.

In order to obtain an equivalent stiffness of the metal foam, k in Eq. (3) can be substituted by

$$\hat{k} = \frac{E_f A}{b/2 \times A} = \frac{2E_f}{b} \tag{4}$$

in which E_f is the metal foam elastic modulus (Fig. 1). This analogy will be used later to establish

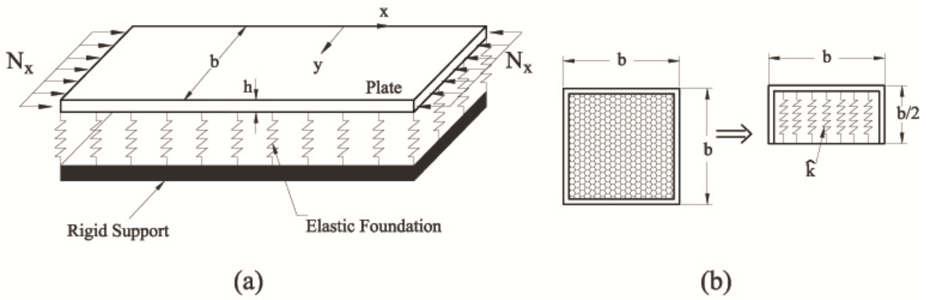

Fig. 1 (a) Geometry of the plate on an elastic foundation (b) Equivalent model for metal foam filled tube

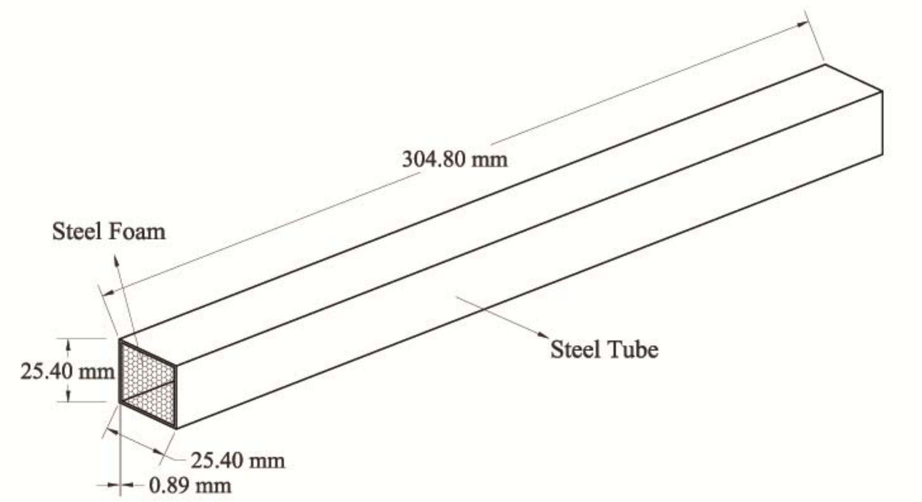

Fig. 2 Geometry of foam filled steel tube which is used in the current study (Fraunhofer 2004)

Table 1 Material properties of the foam filled steel tube used in the current study (Fraunhofer 2004)

Material	Tensile Str. MPa (ksi)	Yielding Str. MPa (ksi)	Elongation %	Elastic Modulus MPa (ksi)	Density (g/cm^3)
Steel	965 (140)	586 (85)	12	203396 (29500)	7.85
Steel Foam	110 (16)	98 (14.2)	3	24132 (3500)	3.92

a bound on the local buckling capacity of a foam filled tube that depends on the material characteristics of the foam. It will be seen later in this study that there is a reasonable agreement between this method and finite element eigenvalue simulation.

3. Finite element modeling

This section presents the procedures and assumptions which are used for finite element modeling of the foam filled tube similar to that used in the experimental study of Fraunhofer USA

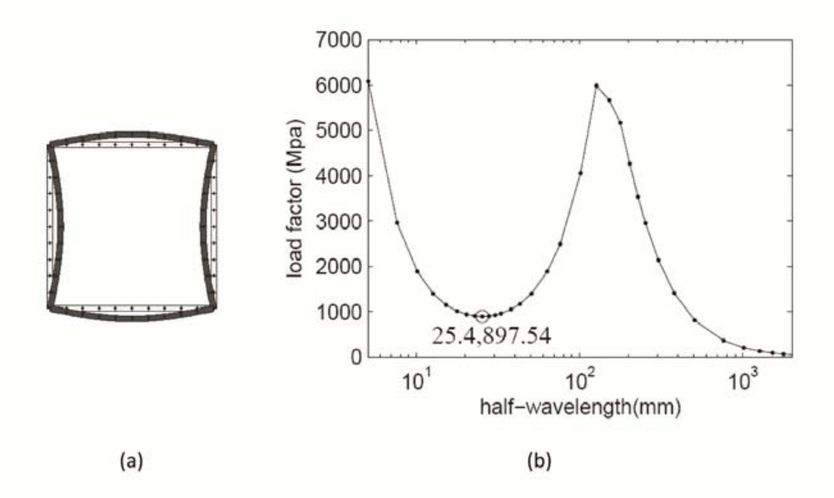

Fig. 3 (a) local buckling shape and (b) load factor in terms of half-wavelength of the empty steel tube

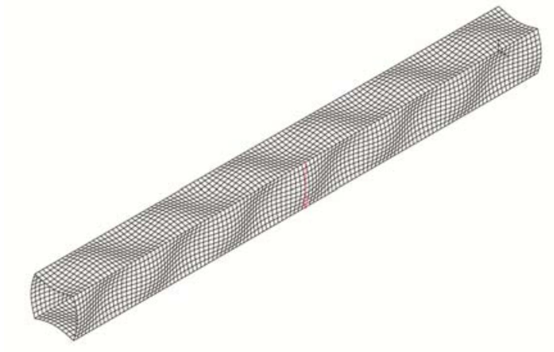

Fig. 4 Empty tube geometry after applying imperfection (the imperfection's scale factor is 10 times bigger than reality)

(Fraunhofer 2004). Fig. 2 shows the dimensions and configuration of the element which was tested in the experimental study. Table 1 shows the properties of the materials that form the test specimen (Fraunhofer 2004)

Numerical modeling is performed within the ADINA framework. The steel foam is modeled by 8-Nodes solid elements and the steel tube is modeled by 4-Nodes shell elements in ADINA.

First, the method for considering geometric imperfections will be described. Then, the different steel foam configurations and composite action which are used in this study will be presented.

3.1 Geometric imperfections

Geometric imperfections are deviations from the nominal geometry which exist in thin walled elements because of the fabrication process. Previous studies show that this imperfection can affect the buckling behavior of the element significantly (Schafer and Pekoz 1998, Graves 1971). Therefore, imperfections should be considered in the finite element modeling.

In general, it can be assumed that the geometry of the local plate imperfections in the cross section is similar to the expected local buckling shape (Tao *et al*. 2009). Therefore, the first step in applying imperfections to the FE model is finding the local buckling shape of the empty steel tube. CUFSM, a semi-analytical finite strip based code, is used to determine the elastic buckling modes of a square steel tube (Schafer and Adany 2006)

Fig. 3 shows the results of the eigenvalue analysis of the square steel tube under uniform axial stress. For a 304.8 mm long steel tube (Fig. 2), the local buckling shape with a half-wavelength equal to 25.4 mm has the lowest corresponding critical load. For this member, therefore, local buckling happens when the total applied axial force becomes equal to 897.4×4×25.4×0.89=81055 N and the buckling shape has a half-wavelength equal to 25.4 mm.

The buckling deformation along the longitudinal direction of the tube is assumed to be sinusoidal. The only remaining parameter needed to specify the steel tube imperfection is the amplitude of the imperfection. One suggestion by previous investigators has been to let the amplitude of the imperfection be **0.01b** in which b is the plate width (GB50018 2002). Fig. 4 shows the geometry of the empty tube after applying imperfection.

3.2 Modeling considerations

In this part of the paper, the assumptions and simplifications made for modeling of the steel foam material and the foam-tube connection will be presented. Moreover, different possible fill configurations of metal foam will be shown.

3.2.1 Material properties

A symmetric, bilinear, elastic perfectly plastic material model is used for the steel foam. Considering that the steel foam is used in this study as a stiffener or thickener, the large strain behavior of the steel foam will not affect the result significantly. Therefore, the assumption of elastic perfectly plastic behavior is acceptable for the purpose of this study.

3.2.2 Composite behavior

One important factor that can influence the behavior of foam filled tubes is the degree of composite action between the foam and the tube. If they are fully bonded to each other, then the foam filled tube will show complete composite behavior substantially bracing the tube walls. If they are unbonded then the foam will brace the walls against inward motion but not against outward motion or shear slippage. In order to model the different degrees of composite action spring elements connecting the tube walls and foam fill are used in ADINA. It can be seen in Fig.5 that three spring elements are defined connecting each node of the tube to the corresponding node on the surface of the solid element mesh representing the steel foam. These springs define the degree of bond in tension, compression and two shear directions.

The springs activated by normal displacement between the tube walls and the foam should always have a very large compression stiffness to simulate contact between the tube and foam. On the other hand, the tensile stiffness of the normal springs and the shear springs can have a range of stiffness from zero to infinity, depending on the degree of bond that is to be modeled. Table 2 shows the spring constant per unit area used for modeling different kinds of composite behavior. The value of the stiffness constant corresponding to partially composite behavior is chosen based on numerical experiments showing that it gives behavior that is intermediate to the fully composite and non-composite cases. In this study the effect of the degree of composite action on the strength

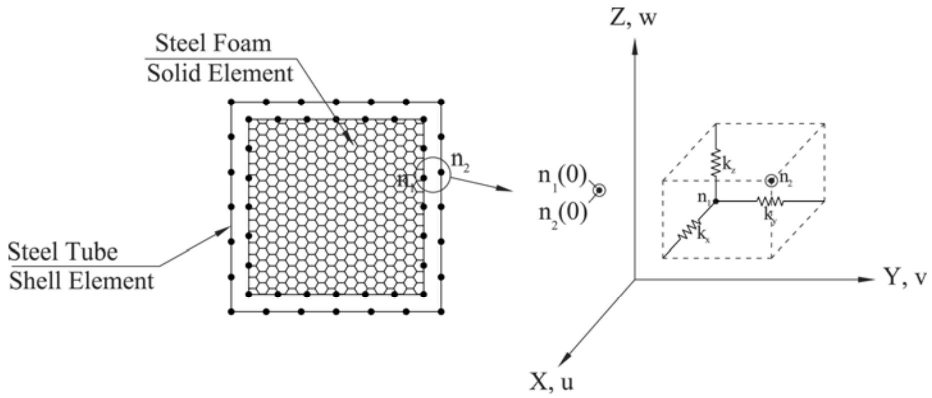

Fig. 5 Configuration of the spring elements in the connection of steel tube to the steel foam

Table 2 Spring constant value for modeling different kinds of composite behavior

Composite Behavior	Fully	Partially	Non
Stiffness Constant (N/mm/mm^2)	> 100000	271.44	0

of the steel foam filled tube is investigated. In a practical construction different degrees of composite action may be attainable depending on the properties of the tube and foam and the means of connecting them.

3.2.3 Geometry

Different possible configurations for the steel foam are shown in Fig. 6. Configurations are sorted into seven groups by the volume of foam used. In order to compare different configurations fairly, configurations with equal volume of steel foam should be compared with each other. The volume of foam used in the configurations increases from group 1 to group 7. Abbreviations are established indicating each configuration throughout the remainder of the paper. In this study, the behavior of each configuration is investigated. Although each configuration may present different challenges in manufacture, the manufacturability of the configurations is not considered this study.

3.3 Loading

Two loading conditions are applied to the foam filled tube in this paper. First, uniform compression is applied to the foam filled tube. In this case both collapse analysis and buckling eigenvalue analysis are performed on the element. Second, a three point bending test is simulated to investigate the effects of the steel foam on the response of the foam filled tube under flexural and shear loading. Moreover, finite element results can be verified by the available experimental result (Fraunhofer 2004). Collapse analysis, using displacement control, is performed in these simulations.

4. Finite element results

In this section of the paper, the results of the finite element simulations are presented including

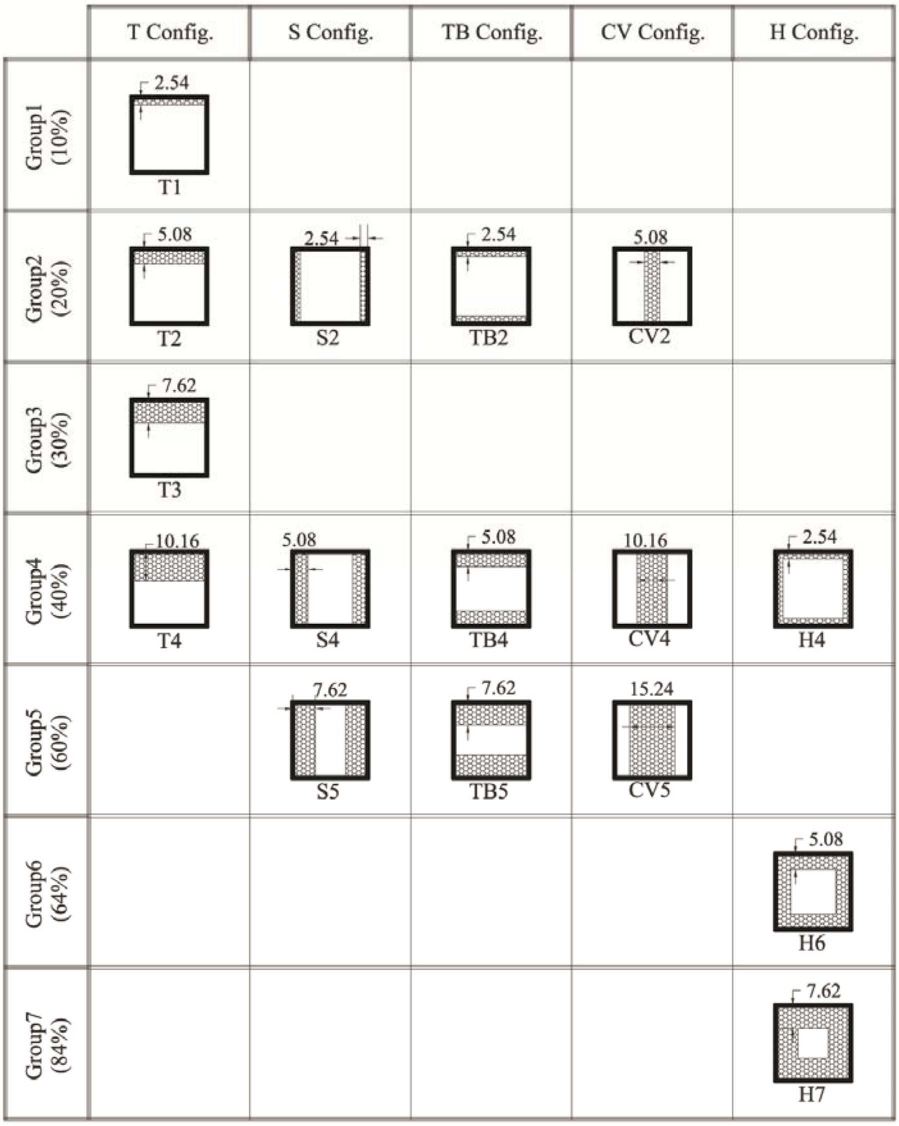

Fig. 6 Configurations of the foam fill tube (All the dimensions are in millimeter and the numbers in the parenthesis are steel foam volume fraction)

the results of the simulations with different steel foam configurations and degrees of composite behavior.

4.1 Uniform compression

One of the load conditions in which tubular cross sections are often used is compression. The doubly symmetric cross section efficiently resists axial forces and combined axial and bending forces. In this section of the paper finite element results for the foam filled tube under uniform

Table 3 The global buckling force and yielding force for the foam filled tube

Configuration	Fully Filled		Empty	
Failure Mode	Global buckling	Yielding	Global buckling	Yielding
Force (kN)	299.13	150.39	210.15	87.16

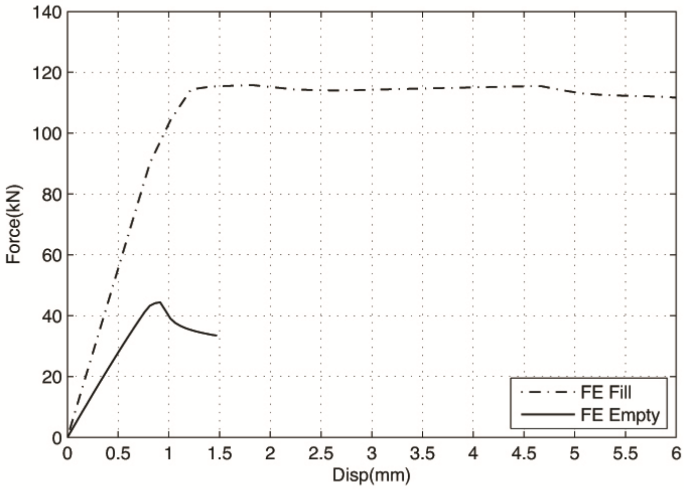

Fig. 7 Pure compression simulation result of the empty steel tube and foam filled tube with non-composite behavior

compression are discussed. In the pure compression condition three failure modes exist: cross section yielding, global buckling and local buckling. Global buckling and yielding forces are given in Table 3 for fully filled and empty tubes. It can be seen that for both the empty tube and the foam filled tube yielding happens at a lower load than global buckling. Therefore, global buckling is not a controlling failure mode.

The local buckling forces of the empty tube are 81.36, 81.05, 80.51 and 44.45 kN using analytical, CUFSM, FE eigenvalue and FE collapse method respectively. The analytical result is calculated by assuming simply supported boundary condition for the tube walls. It can be seen that for the analytical, finite strip (CUFSM) and FE Eigenvalue method, which use the assumption of linear behavior for the materials, the results are essentially identical. The buckling force obtained by FE collapse analysis is smaller than that obtained from other methods due to consideration of material nonlinearity and geometric imperfection. Moreover, the local buckling force is smaller than yielding force in all cases, which shows that wall buckling is the dominant failure mode for the element.

Fig. 7 shows that by simply filling a steel tube with steel foam the buckling force increases from 44.45 kN to 115.80 kN. It shows that steel foam improved the buckling resistance of the steel tube by 260 percent. It also shows a quite different post-buckling behavior in which the foam filled tube can sustain large deformation at constant moment, forming a suitable structural hinge, whereas the moment resisted by the empty tube rapidly degrades after peak moment is reached.

Fig. 8 shows the deformed shape of the empty tube under the pure compression after the collapse and the eigenvalue analysis. It can be seen that dominant buckling mode for both collapse and the eigenvalue analysis have an aspect ratio equal to one which is predicted by the analytical

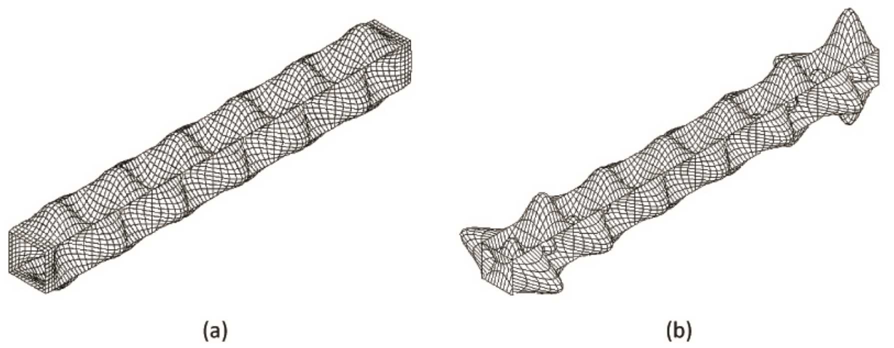

Fig. 8 Deformed shape of the empty tube under the pure compression after (a) collapse analysis (b) eigenvalue analysis

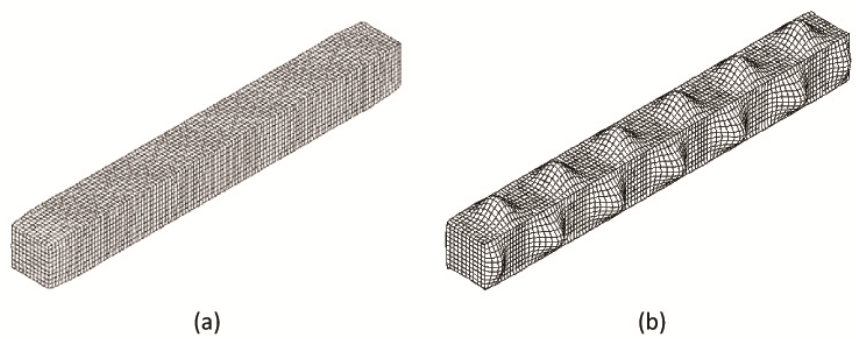

Fig. 9 Deformed shape of the fully filled tube under the pure compression after collapse analysis with (a) fully composite and (b) non composite behavior

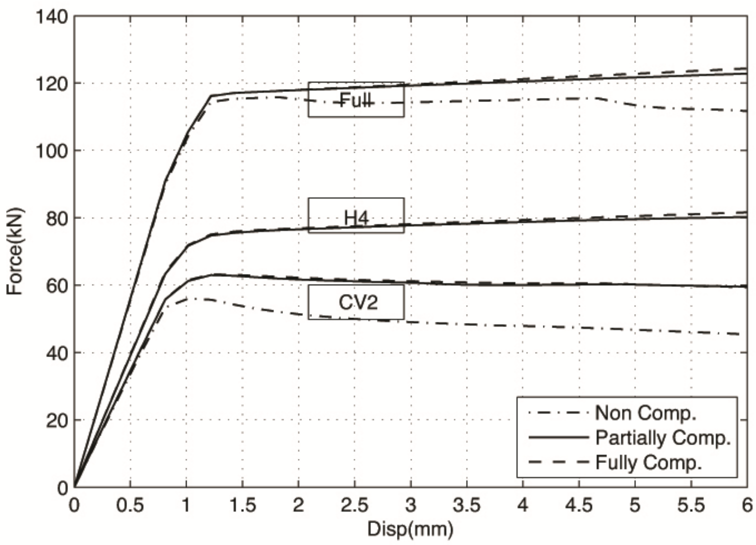

Fig. 10 The effect of the composite behavior on the force-displacement result for different configurations in the pure compression

analysis. For the eigenvalue analysis, deflection is amplified near the end of the tube due to boundary effects that do not significantly affect the critical load.

The deformed shape of the fully filled tube under pure compression with fully composite and non composite behavior is depicted in Fig. 9. It can be seen that the steel foam reduced the amplitude of the deformation for the foam filled tube with non-composite behavior. For the fully composite behavior it can be seen there is no buckling. Failure happens because of material yielding.

4.1.1 The effects of composite behavior

Fig. 10 illustrates how the degree of composite action affects the load-deflection response of the foam filled tube. It can be seen that improving bond between the steel foam and the tube walls will increase the element's strength and that the amount of improvement depends on the foam configuration. The best improvement can be seen in the CV configuration. In the CV configuration, increasing bond stiffness alters the mode shape, leading the cross section to tolerate more force before failure.

4.1.2 The effects of steel-foam configuration

An equitable way to compare different configurations of the foam fill is to categorize them into groups with same foam volume fraction. Fig. 11 shows the force-displacement relations for the pure compression simulation for the three groups of configurations in which the foam volume fraction varies from 20% to 60%. It can be seen that putting steel foam on two sides of the steel tube (S configuration) will improve the buckling behavior of the foam filled tube more than distributing it on all walls (H configuration) or placing it as a center brace (CV configuration).

Figs. 12 - 13 show the effect of the steel foam volume fraction on response of the foam filled tube under pure compression. It can be seen that for foam volume fraction of 40\% and 60\% (groups 4 and 5), the S configuration develops additional post yielding capacity while there is no

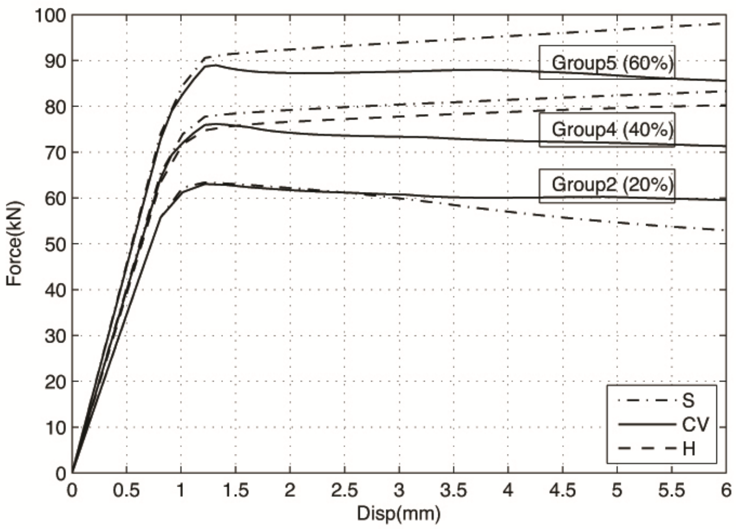

Fig. 11 The force-displacement result of the pure compression simulation for the three groups of configurations with constant volume fraction and partially composite behavior

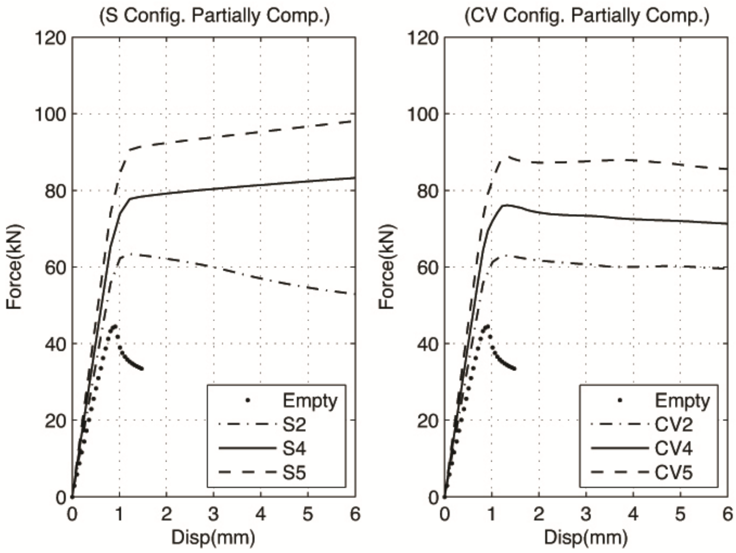

Fig. 12 The force-displacement result of the pure compression simulation for S and CV configurations with different volumes of steel foam

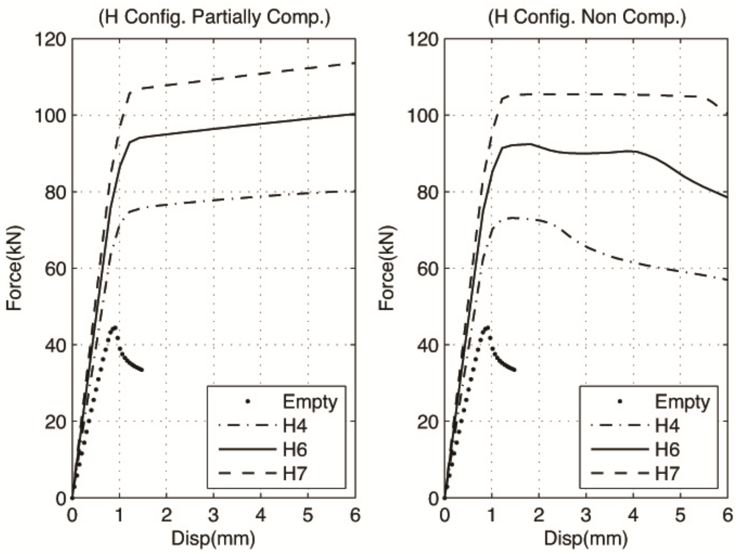

Fig. 13 The force-displacement result of the pure compression simulation for H configurations with different volumes of steel foam

additional post yielding capacity in the CV configuration. This can be interpreted to mean that the collapse mechanism in the S configuration is dominated by cross section yielding while in the CV configuration, local instability plays a greater role in defining the post yield response and prevents the development of additional post-yield capacity. Fig. 13 illustrates that in the H configuration changing the behavior from non-composite to partially composite will change the collapse mode from one dominant by local instability to one dominant cross section yielding. This is shown by the lack of a descending branch in the load displacement curve in the H configurations with partially composite behavior shown in Fig. 13.

4.1.3 The effects of metal-foam elastic modulus

In this part of the paper, the effect of metal foam elastic modulus on the buckling load of the fully foam-filled tube is investigated. The result of FE simulation of the metal-foam filled steel tube under pure compression can be compared to an approximate analysis that uses the solution for the critical load of a plate on an elastic foundation. Considering that the theory of instability of plates on elastic foundations, which is presented in previous parts of the paper, assumes elastic material behavior, the appropriate comparison is between the approximate analysis and linear eigenvalue analysis of the foam filled tube.

Fig. 14 shows the variation of buckling load with metal foam elastic modulus. It can be seen that there is reasonable agreement between the approximate analytical result and the FE eigenvalue simulation. For increasing elastic modulus of the metal foam the analytical solution gives more conservative predictions than the FE simulation yet both predict substantially higher capacity than the plastic collapse analysis. The disagreement comes from the fact that the approximate analytical solution neglects changes in the mode shape that occur at higher elastic moduli. Therefore it can be seen that the theory of the behavior of plates on elastic foundations can provide a conservative prediction of the elastic buckling load of the foam filled tube (Fig. 14). It should be mentioned that when the elastic modulus reaches E=350 Mpa the buckling mode changes to a global mode with critical load equal to 219 kN.

4.2 Three point bending test

The ability of a foam filled tube to absorb more energy then and increase the bending strength of an empty steel tube will be investigated in this section of the study. These properties are illustrated through simulations of three point bending tests of foam filled tube with different steel foam fill configurations and degrees of composite action.

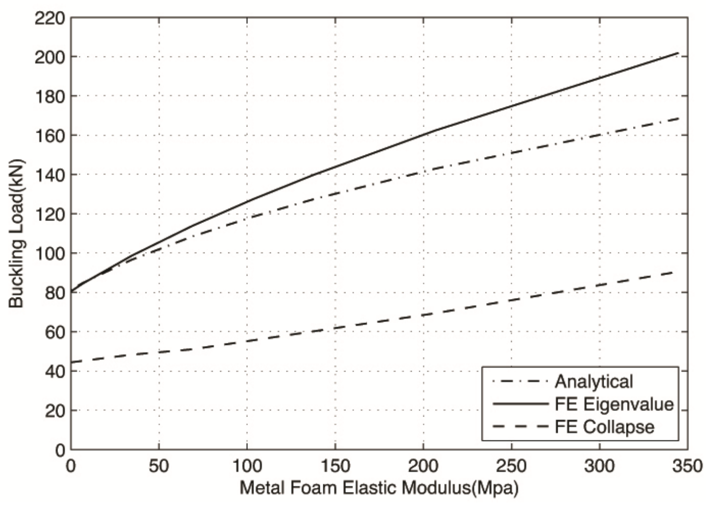

Fig. 14 The variation of buckling load in terms of metal foam elastic modulus

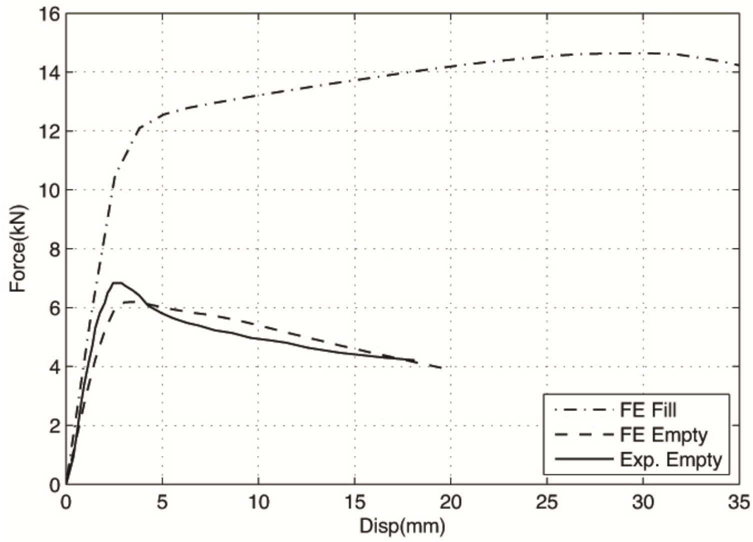

Fig. 15 Three point bending test result of the empty steel tube and foam filled tube with non-composite behavior

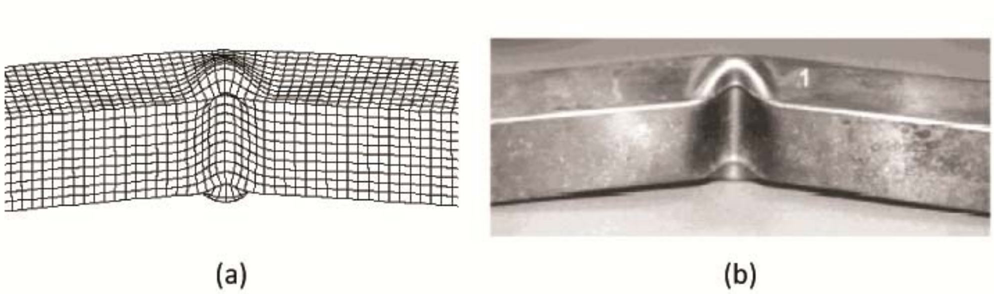

Fig. 16 Deformed shape of the empty steel tube after (a) finite element simulation and (b) experimental test (Fraunhofer 2004)

4.2.1 Finite element model verification

The use of plastic collapse analysis is well validated as a means for evaluating the strength of thin walled structural members. Fig. 15 shows three-point bending test results for an empty tube (experiment and simulation) and a foam filled tube with no bond between the fill and tube walls (simulation only). It can be seen that the experimental and simulated force displacement curves are similar for the empty tube, which confirms that the FE model is working properly.

Moreover steel foam improved the buckling resistance of the steel tube by 240 percent. Fig. 15 also shows a quite different post-buckling behavior in which the foam filled tube can sustain large deformation at constant moment, forming a suitable structural hinge, whereas the moment resisted by the empty tube rapidly degrades after peak moment is reached.

Fig. 16 shows the deformed shape of the empty tube after the experiment and FE simulation. Reasonable similarities can be seen in the deformed shapes. In both cases, there is an inward fold on the compression surface, which arises as a result of local instability in the compression flange.

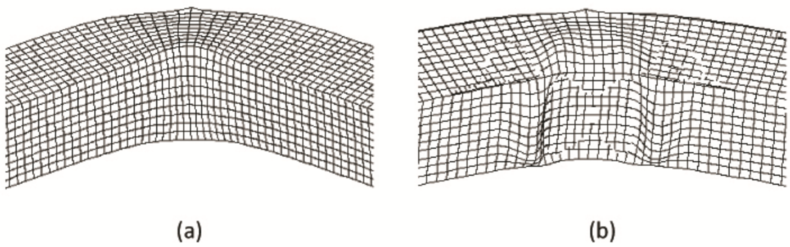

Fig. 17 Deformed shape of the foam filled tube with (a) fully composite and (b)non-composite behavior

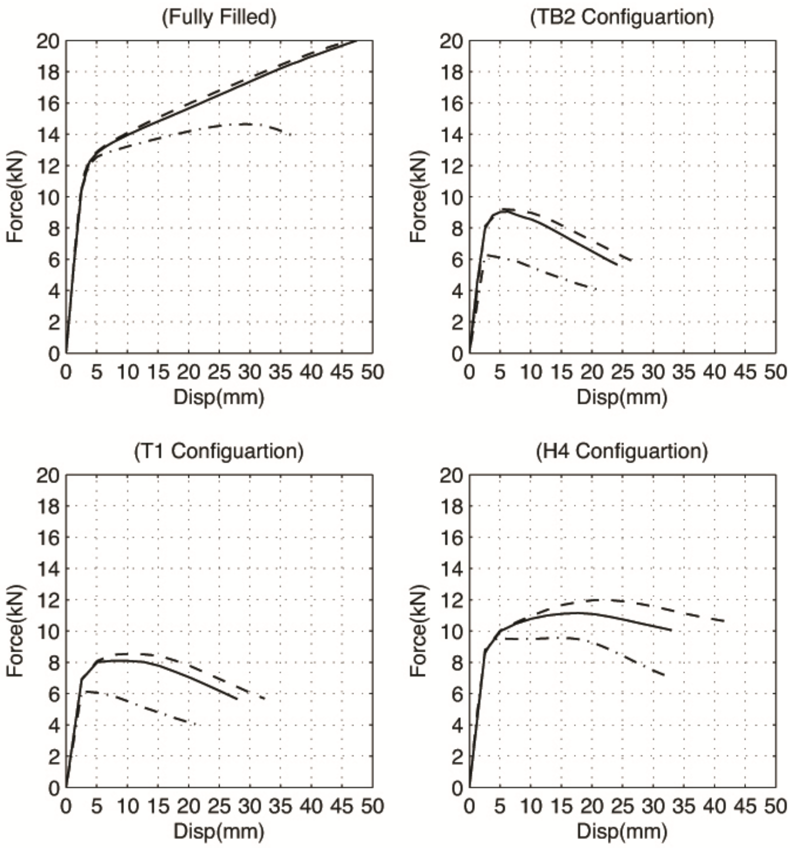

Fig. 18 The effect of the composite behavior on the force-displacement result for different configurations in three point bending test (-.- non composite , - partially composite , - - fully composite)

4.2.2 The effects of composite behavior

The degree of composite action between the steel foam fill and the walls of the tube is one of the factors which can affect the response of the composite element.

Fig. 17 shows the deformed shape of the foam filled tube after collapse with non-composite and fully composite behavior. It can be seen that in the beam with fully composite behavior, failure happens due to full cross section yielding and no local buckling occurs, but in the beam with non-composite behavior local buckling of the compression flange is the primary failure mode. Note that the mode shape differs from that of Fig.16 and agrees well with that reported in (Fraunhofer 2004)

Fig. 18 shows the effects of composite behavior on the behavior of tubes with different fill configurations. It can be seen that the strength of the composite member is quite sensitive to the degree of composite action and that only for fully filled tubes is local buckling of the tube walls fully mitigated.

4.2.3 The effects of steel-foam configuration

As was described in the previous section, sixteen configurations of foam fill with different steel foam volumes are chosen to investigate the effect of fill configuration on response. Groups 2, 4, and 5 are selected to study the effect of the configuration on the response. Fig. 19 shows the force-displacement results of the three point bending test simulation for the three configuration groups. Moreover, Tables 4 - 5 show the strength and absorbed energy of the foam filled tube in the three-point bending test simulation for the three configurations, respectively. The absorbed energy is calculated as the area under the force displacement curve up to the point of peak load. All the results in this section are calculated for partially composite behavior.

It should be mentioned that the maximum strength of the different configurations is limited by plastic moment of the foam filled tube which corresponds to an applied force of 27.89 kN for a fully filled tube. All results shown in Figs. 18-19 represent the onset of instability except for the result of the fully filled tube.

It can be seen that for group 2, which has the lowest foam volume fraction, the T configuration shows the highest strength and greatest absorbed energy. In this group, the strength of the S, CV

Table 4 Strength of the foam filled tube in the three-point bending simulation for the three groups of configurations with partially composite behavior

Group	Strength (kN)				
2	T2	S2	TB2	CV2	
(20%)	11.69	9.21	9.04	9.95	
4	T4	S4	TB4	CV4	H4
(40%)	12.38	13.95	14.12	13.09	11.16
5		S5	TB5	CV5	
(60%)		16.47	18.92	16.62	

Table 5 Absorbed energy in the three-point bending simulation of the foam filled tube for the three groups of configurations with partially composite behavior

Group	Energy (kN.mm)				
2	T2	S2	TB2	CV2	
(20%)	317.4	183.6	44.2	147.6	
4	T4	S4	TB4	CV4	H4
(40%)	358.7	718.3	395.8	388.2	171.8
5		S5	TB5	CV5	
(60%)		843.5	1437.1	1245.2	

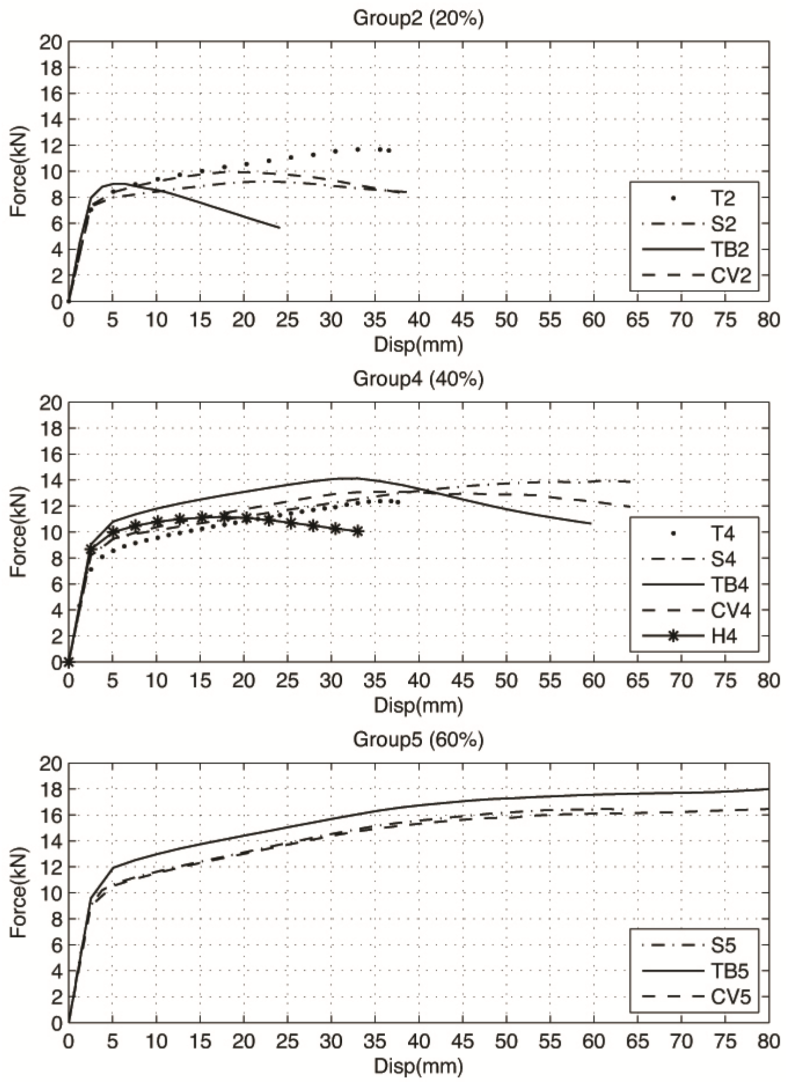

Fig. 19 The force-displacement result of the three point bending test for the three groups of configurations which have partially composite behavior

and TB configurations are very similar, but, the CV and S configuration are more ductile than the TB configuration absorbing more energy and reaching peak load at a larger displacement. The TB configuration is stiffer because it has higher moment of inertia than the other configurations. There are five configurations in group 4. It can be seen that the T configuration is not the optimum configuration in this group. The TB4 and S4 configurations have the highest strength. The H4 configuration has the lowest strength and the least ability to absorb energy. The S4 configuration is the most ductile configuration in this group. The amount of absorbed energy in the S4 configuration is close to twice as much as in other configurations. There are three configurations in group 5, S3, TB3 and CV3. Although, the S configuration performs well in groups 2 and 4, it has the lowest strength and energy absorption ability in group 5.

Fig. 20 shows the effect of the steel foam volume fraction in 4 different configurations on the response. In this figure force displacement response is shown for different steel foam volumes ranging from an empty tube to a fully filled tube. It can be seen that in the T configuration the strength increases from 6.2 kN in the empty tube to 11.69 kN even when only a 5.08mm thickness of steel foam is placed under the top wall. Moreover, the absorbed energy increases from 14.83 kN.mm in the empty tube to 317.4 kN.mm in the T2 configuration. Increasing the steel foam volume from the T2 configuration to the T4 configuration, however does not change the force-displacement behavior significantly. Although initially adding a small amount of steel foam under the compression flange will significantly increase the strength and ability to absorb energy in the steel tube, continuously adding steel foam in this configuration is of little benefit.

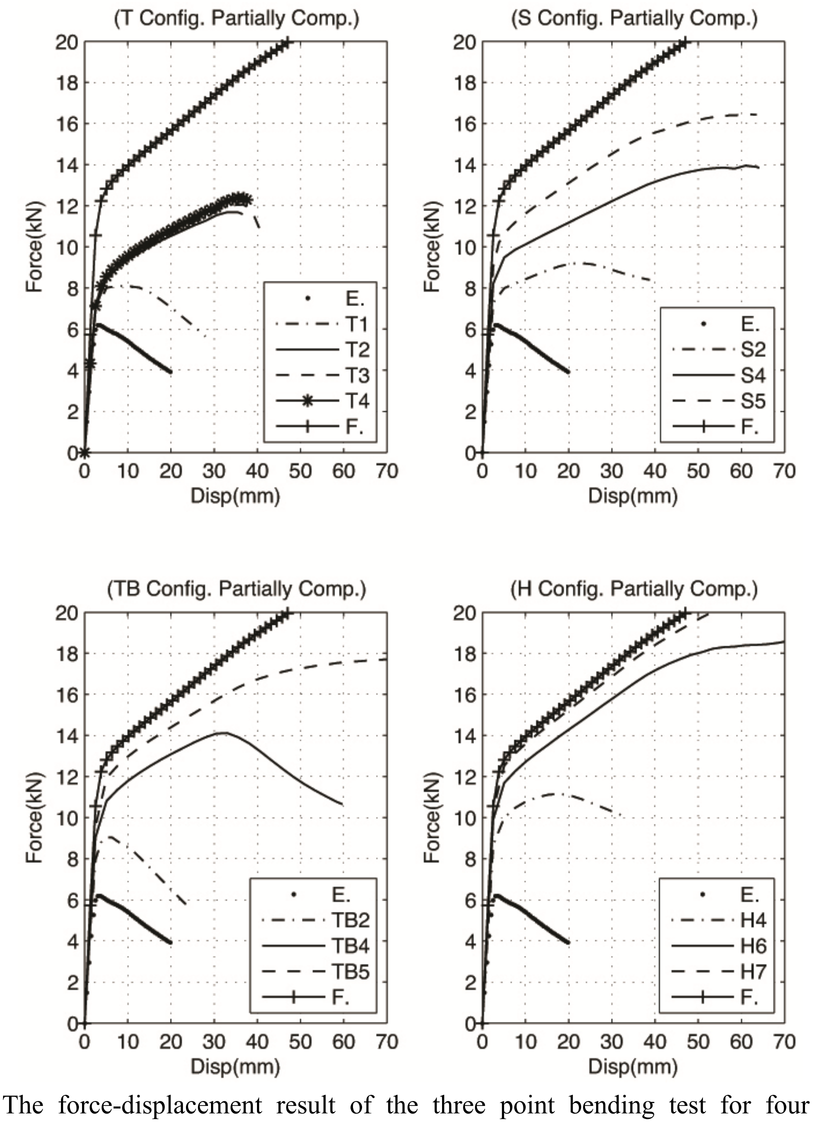

Fig. 20 The force-displacement result of the three point bending test for four different configurations with different volumes of steel foam

Table 6 P_u/P_y in the three-point bending simulation of the foam filled tube for the three groups of configurations with partially composite behavior

Group	P_u/P_y				
2	T2	S2	TB2	CV2	
(20%)	1.66	1.27	1.14	1.35	
4	T4	S4	TB4	CV4	H4
(40%)	1.74	1.7	1.56	1.6	1.29
5		S5	TB5	CV5	
(60%)		1.82	1.97	1.85	

In the TB and S configurations, increasing the volume of steel foam will increase the strength and the absorbed energy almost linearly. In the H configuration increasing the steel foam volume fraction is of less benefit to the response.

In summary, the optimal configuration of the steel foam fill depends on the available volume of steel foam to be used in the composite member. Very substantial improvement in performance can be obtained through the deployment of a relatively small amount of foam under the compression flange.

One other way to evaluate the performance is to calculate the ratio of maximum strength to yielding strength in the different configurations. This ratio is the sign of element residual capacity after yielding. Table 6 shows this ratio for the different configurations with partially composite behavior. It can be seen that the post yield capacity of the element is dramatically increased by the addition of small amounts of material in the T2 and T4 configurations.

5. Conclusions

Although steel foam is a highly compliant material that lacks strength in comparison to solid steel, it can be deployed in a composite fashion to significantly improve strength and ductility of thin-walled tubes. These improvements are obtained both in compression and bending. Moreover, if composite action between steel foam and steel increases, the strength of the element will improve such that the failure mode change from local buckling to cross section yielding. The response is sensitive to the configuration of the foam fill and the optimal configuration depends on the fraction of the interior volume that is to be filled. If only a small fraction of the interior volume is to be filled, the best performance improvement is obtained by placing the foam in contact with any walls loaded in compression. Note that we consider monotonic loading and the consideration of loading reversal would necessitate other foam fill configurations.

References

Ashby, M., Evans, A., Fleck, N., Gibson, L., Hutchinson, J. and Wadley, H. (2000), *Metal Foams: A Design Guide*, Butterworth-Heinemann, Elsevier Science (USA).

Chacon, R., Mirambell, E. and Real, E. (2013), “Strength and ductility of concrete-filled tubular piers of integral bridges”, *J. Construct. Steel Res.*, **46**, 234-246.

Chajes, A. (1974), *Principles of Structural Stability Theory*, Prentice-Hall.

Chen, C.C., Ko, J.W., Huang, G. and Chang, Y.M. (2012), “Local buckling and concrete confinement of concrete-filled box columns under axial load”, *J. Construct. Steel Res.*, **78**, 1836-1845.

Chitawadagi, M. and Narasimhan, M. (2009), “Strength deformation behavior of circular concrete filled steel tubes subjected to pure bending”, *J. Construct. Steel Res.*, **65**(8-9), 1836-1845.

Furlong, R.W. (1967), “Strength of steel-encased concrete beam-columns”, *J. Struct. Div.*, ASCE **93**(5), 113-124.

GB50018, (2002), *Technical code of cold-formed thin-wall steel structures*. (in Chinese)

Gibson, L. and Ashby, M. (1999), *Cellular Solides: Structure and Properties*, Second Edition, Cambridge University Press, Cambridge, United Kingdom.

Graves Smith, T.R. (1971), “The effect of initial imperfections on the strength of thin-walled box columns”, *Int. J. Mech. Sci.*, **13**, 911-925.

Han, L.H. (2004), “Flexural behaviour of concrete-filled steel tubes”, *J. Construct. Steel Res.*, **60**(2), 313-337.

Kremer, K., Liszkiewicz, A. and Adkins, J. (2004), *Development of Steel Foam Materials and Structures, by Fraunhofer USA*, Delaware, October.

Lu, F.W., Li, S.P., Li, D.W. and Sun, G. (2007), “Flexural behavior of concrete filled non-uni-thickness walled rectangular steel tube”, *J. Construct. Steel Res.*, **63**(8), 1051-1057.

Moradi, M., Arwade, S.R. and Schafer, B.W. (2013) “Computational evaluation of limit states of thin-walled channels made from steel foam”, *Thin Wall. Struct.,* **62**, 206-214.

Prion, H.G.L. and Boehme, J. (1994), “Beam-column behavior of steel tubes filled with high strength concrete”, *Can. J. Civil Eng.*, **21**, 207-218.

Schafer, B.W. and Adany, S. (2006), “Buckling analysis of cold-formed steel members using CUFSM: conventional and constrained finite strip methods” *Eighteenth International Specialty Conference on Cold-Formed Steel Structures*, Orlando, FL, October.

Schafer, B.W. and Pekoz, T. (1998), “Computational modeling of cold-formed steel: characterizing geometric imperfections and residual stresses”, *J. Construct. Steel Res.*, **47**, 193- 210.

Schneider, S.P. (1998), “Axially loaded concrete-filled steel tubes”, *J. Struct. Eng.*, **124**(10), 1125-1138.

Seide, P. (1958), “Compressive buckling of a long simply supported plate on an elastic foundation”, *J. Aeronaut. Sci.*, **27**, 382-392.

Shakir-Khalil, H. and Mouli M. (1990), “Further tests on concrete-filled rectangular hollow-section columns”, *Struct. Eng.*, **68**(20), 405-413.

Smith, B.H., Szyniszewski, S., Hajjar, J.F., Schafer, B.W. and Arwade, S.R. (2012) “A review of steel foam processing, properties, and applications”, *J. Construct. Steel Res.*, **71**, 1-10

Szyniszewski, S., Smith, B.H., Hajjar, J.F., Arwade, S.R., Schafer, B.W. (2012), “Local buckling strength of steel foam sandwich panels”, *Thin Wall. Struct.*, **59**, 11-19.

Tao Z., Uy B., Han L. and Wang Z. (2009), “Analysis and design of concrete-filled stiffened thin- walled steel tubular columns under axial compression”, *Thin Wall. Struct.*, **47**, 1544-1556.

Varma, A.H., Ricles, J.M., Sause, R. and Lu, L.W. (2002), “Seismic behaviour and modeling of high-strength composite concrete-filled steel tube (CFT) beam-columns”, *J. Construct. Steel Res.*, **58**(5-8), 725-758.