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Experimental and Numerical Behavior of Tubular Foam Filled Struts

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ABSTRACT

This paper presents an investigation for the behavior of foam filled circular steel tubes under static axial loads through numerical and experimental test program. Six specimens were included in the experimental test program divided into three groups. The tubes were of different diameters, wall thickness and different lengths. One tube of each group was filled with Polyurethane (PU) foam with density of 30 kg/m^3. All specimens were exposed to axial compression using compression test machine. Numerical simulation was also conducted and the results showed good agreement with experimental tests. Results conclude that there was no effect in the load carrying capacity by using lower foam density filling steel column, but there was an increase in the load carrying capacity by using construction foam (metallic foam). The results also showed noticeable reduction in local buckling phenomenon besides a more ductile behavior for this type of elements.

الملخص:

هذا البحث يدرس سلوك الأعمدة المعدنية المعبأة بالفوم تحت تأثير الأحمال الإستاتيكية من خلال الأختبارات المعملية و النظرية. جميع العينات المختبرة عبارة عن اسطوانات صلب دائرية وعددها 6 عينات مقسمة الى 3 مجموعات. المجموعة الأولى عينتين ذات قطر 112 مم وسمك 2 مم وطول 200 مم ، المجموعة الثانية عينتين ذات قطر 112 مم وسمك 2 مم وطول 300 مم، المجموعة الثالثة ذات قطر 220 مم وسمك 2.5 مم وطول 200 مم. يتم ملئ عينة من كل مجموعة بفوم البولي يوريثان بكثافة مقدارها 30 كجم/م3. جميع العينات تم التأثير عليها بحمل ضغط محوري باستخدام ماكينة الضغط. تم عمل تحليل نظري للعينات باستخدام برنامج الأباكوس وكانت نتائجه متوافقة مع النتائج العملية. أظهرت النتائج عدم تأثير الفوم ذو الكثافة المنخفضة في زيادة قدرة تحمل الأعمدة بينما كان هناك زيادة في قدرة تحمل الأعمدة عند استخدام الفوم الإنشائي (الفوم المعدني). أيضاً أظهرت النتائج انخفاض ملحوظ لظاهرة الانبعاج المحلي بالإضافة إلى حدوث زيادة في الممطولية لهذا النوع من الأعمدة.

1. INTRODUCTION AND LITERATURE REVIEW.

In many fields, the desired material needs to be both light weight and strong for functionality, while economic considerations require characteristics of low cost and ease of manufacturing. Foam-filled structures have been developed as a way to increase the flexural rigidity of a structure while minimizing the associated weight such as foam-filled steel tubes. Several researches presented and discussed the behavior and performance of foam-filled steel tubes through experimental and numerical investigations. The initial studies on the effectiveness of filling thin-walled columns with low-density foams were carried out with polyurethane foams. Thornton [1] indicated that a significant increase in the energy absorption could be achieved through foam filling. However, foam filling was not weight effective unless columns made of high-density low-strength alloy with thin walls are used. Reid *et al*. [2] conducted static and dynamic tests on thin-walled metallic tubes. They observed that the increase in energy absorption was not only due to the added strength of the foam but also due to the interaction of foam with the enveloping tube sheet. More recently, extensive studies have been carried out by many authors on introducing ultra-light aluminum foams or aluminum-honeycomb fillers into hollow structural members. Seitzberger *et al*. [3, 4] carried out experimental and numerical studies on the axial crushing of steel columns filled with 15-25% relative density aluminum foam. For the various sections investigated a significant increase in specific energy absorption (approximately 50%) was observed when foams are used.

In this research, the foam is used as a filling material for steel tubes to decrease the tendency of tube walls for local buckling and at th7e same time to share the axial load with the steel section leading to more savings in steel material.

2. EXPERIMENTAL PROGRAM AND TEST SETUP

2.1 Experimental program description

A total of six specimens were prepared using circular mild steel tubes, two specimens have a thickness of 2 *mm*, 112 *mm* diameter and 200 *mm* length. The second two specimens have a thickness of 2 *mm*, 112 *mm* diameter and 300 *mm* length. The last two specimens have a thickness of 2.5 *mm*, 220 *mm* diameter and 200 *mm* length. Three specimens were empty and the corresponding three specimens were filled with PU (Polyurethane) foam of 30 kg/m^3 capacity.

Fig.1:Test setup of specimen.

Table.1 summarizes the properties and details of specimens. The first two specimens with thickness of 2 *mm*, 112 *mm* diameter and 200 *mm* length were labeled as E1and F1 (empty and filled; respectively). The second two specimens with thickness of 2 *mm*, 112 *mm* diameter and 300 *mm* length were labeled as E2and F2 (empty and filled; respectively). The last two specimens with thickness of 2.5 *mm*, 220 *mm* diameter and 200 *mm* length were labeled as E3 and F3 (empty and filled; respectively).

Table 1. Properties and details of specimens

Specimen	**Tube dimensions**			**Area of tube A_{st}**
	D	***T***	***L***	
E1 and F1	112.0	2.0	200.0	690.80
E2 and F2	112.0	2.0	300.0	690.80
E3 and F3	220.0	2.5	200.0	1,707.37

* D is the external diameter

2.2 Preparation of physical models

The foam used in filling the steel tubes had a density of 30 kg/m^3. The steel tubes were made of mild steel with 360 *MPa* yield strength (f_y) and a Poisson's ratio of 0.3.

2.3 Test setup and instrumentation

The tests in this study were carried out in the laboratory of Menoufia University Faculty of Engineering using a compressive machine of 2,000 *KN* Capacity. The specimens were prepared in the testing machine as shown in figure 1. One transducer (LVDT) was used to measure the axial displacement.

2.4 Test procedures

The load was applied to the specimens in the form of axial uniform compression over the foam and steel tube. The load was applied in a slow rate to avoid any high strain rates effects. The LVDT and load readings were checked carefully and recorded while loading was being applied to the specimens within the elastic limit. The load was applied at 10 *KN* intervals in order to have sufficient data points to delineate load-displacement curves. After the immediate drop of the load due to local buckling, the test continued as the load stabilized until the load started again to increase slightly when the test was ended. Then the specimen was removed and carefully examined after the test.

3. EXPERIMENTAL RESULTS

The axial load against axial displacement curves of foam-filled tubular steel column specimens was drawn to discuss their behavior.

Table 2 shows foam density, cross section area of specimens and load capacity of specimens. The experimental load- displacement curves for all specimens are shown in figures 2, 3 and 4.

Table. 2: Foam density, cross section area of specimens and load capacity of specimens.

Specimen	Foam ρ_f (kg/m^3)	Steel f_y (MPa)	Area of steel A_s (mm^2)	P_{test} (KN)
E1	-----	360	690.80	185.0
E2	-----	360	690.80	184.0
E3	-----	360	1707.37	432.0
F1	30	360	690.80	185.0
F2	30	360	690.80	184.0
F3	30	360	1,707.37	432.0

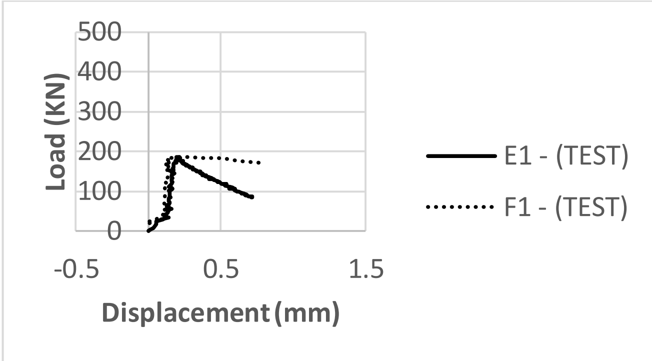

Fig. 2: Experimental load-displacement curves for specimens E1and F1.

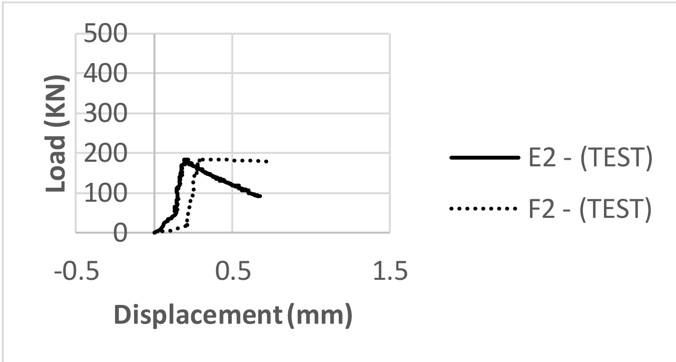

Fig.3: Experimental load-displacement curves for specimens E2 and F2

The experimental results of samples E2 and F2 (both empty and filled) have more displacement in the initial stage than the theoretical results of Abaqus compared to the results of the other samples. This is attributed to the fact that these samples are longer than the other samples and practically it was difficult to align their ends perfectly to the loading plates.

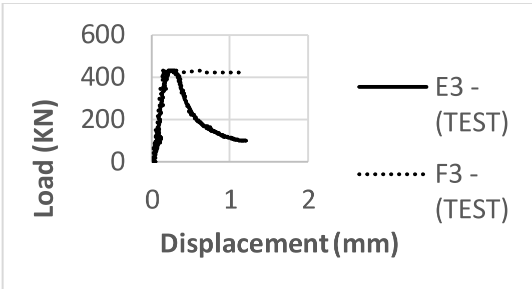

Fig. 4: Experimental load-displacement curves for specimen E3 and F3.

Figure 5 shows the failure mode of specimens and deformed shape at failure. It can be seen that both ends of the steel tube have locally buckled at failure under the loading plates. Also, by examining the specimen, the foam was crushed. Therefore, the failure mode was confined foam crushing and local buckling failure mode.

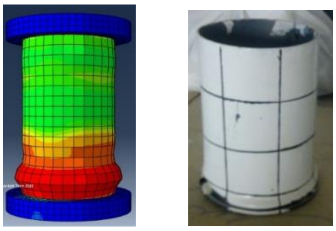

Fig. 5: Experimental and numerical failure mode of the column E1.

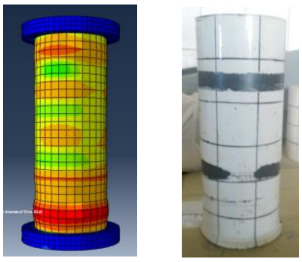

Fig. 6: Experimental and numerical failure mode of the column E2.

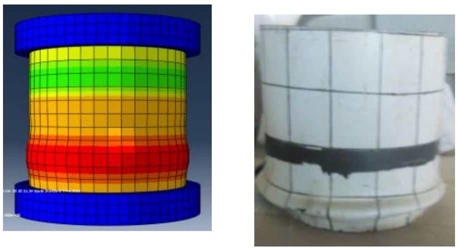

Fig. 7: Experimental and numerical failure mode of the column E3.

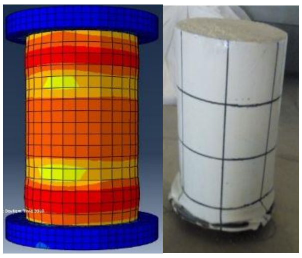

Fig. 8: Experimental and numerical failure mode of the column F1.

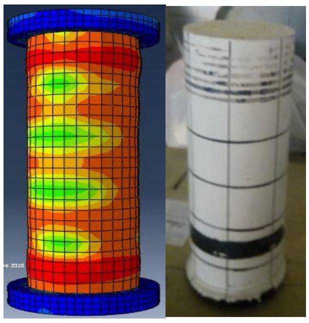

Fig. 9: Experimental and numerical failure mode of the column F2.

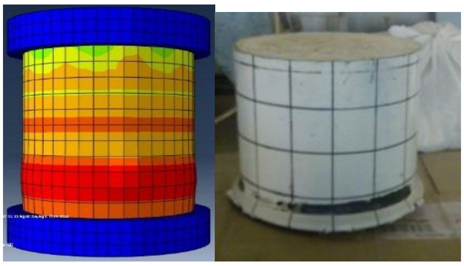

Fig. 10: Experimental and numerical failure mode of the column F3.

4. NUMERICAL ANALYSIS

4.1 Validation of numerical model

4.1.1 General considerations

The main objective of this study is to develop an accurate finite element model to simulate the behavior of circular columns filled with foam. The finite element program ABAQUS [5] was used in current study. FE model depends on defining the foam, the steel tube, the interface between the foam and the steel tube, the choice of the element type, mesh size, boundary condition and load application.

4.1.2 Finite Element Type and Mesh

The steel tube was simulated by using the 4-noded doubly curved shell elements with reduced integration S4R. Fine mesh of three-dimensional 8-Node solid elements (C3D8) is used to model the foam infilled and two end plates.

4.1.3 Boundary Conditions and Load Application

All degrees of freedom for the top and bottom surfaces of columns were prevented except for the displacement at the loaded end, which is the top surface, in the direction of the applied load. The STATIC option in ABAQUS was used to apply the load. The load was applied in increments using the modified RIKS method available in the ABAQUS library. The load will be defined as uniform load using PRESSURE option which is used to apply uniform load in the top surface of the upper plate.

4.1.4 Material Modeling of the Foam

The stress-strain curve can also be distinguished in two parts (elastic part and plastic part). The linear part in the stress-strain curve of the foam was defined by The ELASTIC option in ABAQUS. The elastic part properties are completely defined by giving the Young's modulus and the Poisson's ratio which was taken equal to 0.2. The plastic part of foam was modeled using the CRUSHABLE FOAM model with isotropic hardening available in ABAQUS [5].

4.1.5 Modeling of steel tube

The modeling of the steel material requires defining the density, which was taken as $7.85*10^{-9}$ *ton /mm*^{3}, the linear part in the stress-strain curve of steel and nonlinear part of the curve. The elastic properties are completely defined by giving the Young's modulus, *E*, and the Poisson's ratio, the values of 210,000 *MPa* and 0.3; respectively. The nonlinear part of the stress-strain curve of steel material was modeled using the PLASTIC option available in ABAQUS [5].

4.1.6 Modeling of foam–steel tube interface

The SURFACE INTERACTION option in ABAQUS was used to create surface interaction properties. The surface interaction properties governed contact interactions. The interaction type was surface to surface contact. The main property needed was the friction between the two faces which is maintained as long as the surfaces remained in contact. The parameters considered in this contact are tangential behavior and friction coefficient.

4.2 Validation process

The experimental and finite element results were compared to verify the finite element model. Comparisons were performed between the ultimate loads obtained from the tests (P_{Test}) and those obtained from the finite element analysis ($P_{F.E}$) as presented in Table 3. It can be seen that good agreement was achieved between the experimental and numerical results.

Table.3. The experimental and finite element load capacity of specimens Properties and details of specimens

Specimen	Tube dimensions			P_{Test} (*KN*) PTest (KN)	$P_{F.E}$ (*KN*) P FE (KN)	P_{Test} /$P_{F.E}$
	D (*mm*)	T (*mm*)	L (*mm*)			
E1	112.0	2.0	200	185	176.0	1.05
E2	112.0	2.0	300	184	175.0	1.05
E3	220.0	2.5	200	432	415.6	1.04
F1	112.0	2.0	200	185	176.4	1.05
F2	112.0	2.0	300	184	175.5	1.05
F3	220.0	2.5	200	432	416.5	1.04

The experimental and numerical load-displacement relationships for specimens E1, E2, E3, F1, F2 and F3 were obtained as shown in Figures 11 to 16; respectively. It was found that good agreement exists between the experimental and numerical deformed shapes of the columns. The failure mode observed experimentally confirmed the numerical prediction, which was mainly local buckling of the steel tube as well as crushing of the foam.

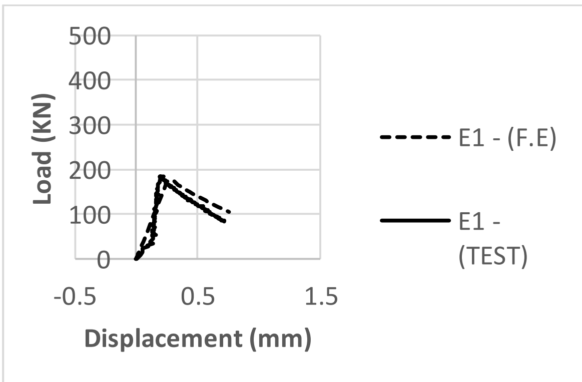

Fig.11: Experimental and numerical load-displacement for specimen E1.

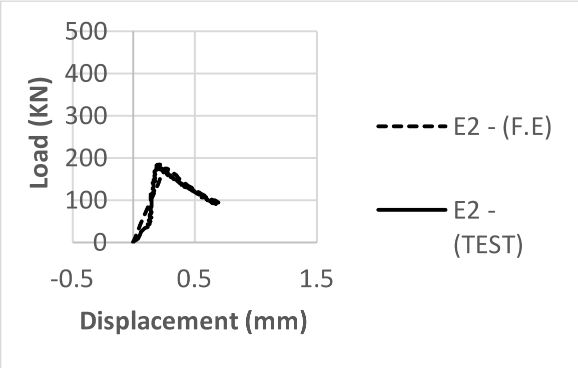

Fig. 12: Experimental and numerical load-displacement for specimen E2.

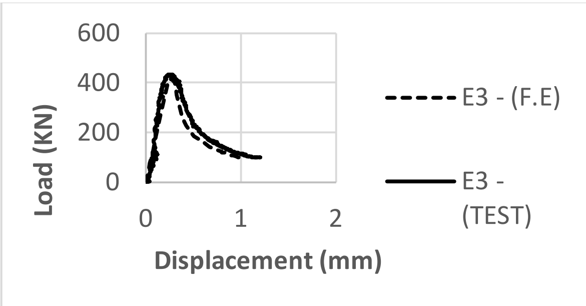

Fig. 13: Experimental and numerical load-displacement for specimen E3.

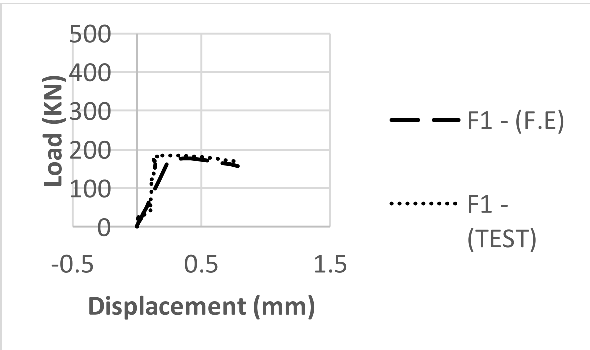

Fig. 14: Experimental and numerical load-displacement for specimen F1.

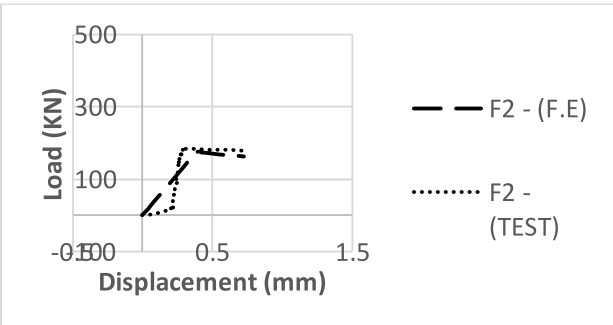

Fig.15: Experimental and numerical load-displacement for specimen F2.

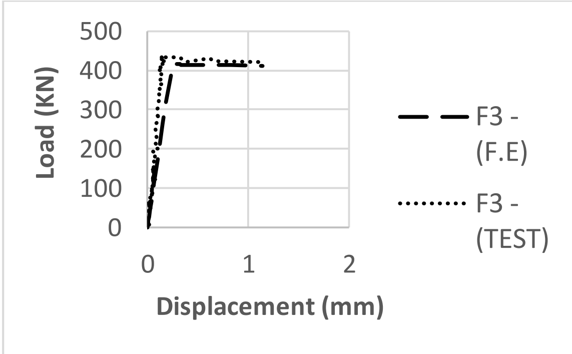

Fig.16: Experimental and numerical load-displacement for specimen F3.

4.3 Parameters of numerical study

Parametric study was performed using finite element to investigate the effect of using structural foam (metallic foam) inside circular columns. The density of the used foam in ABAQUS was 810 kg/m^3.

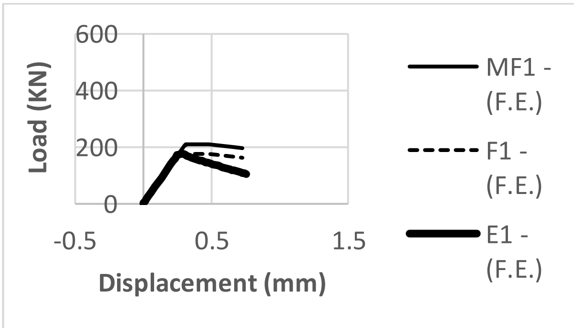

Fig.17: Numerical load-displacement for specimens E1, F1 and MF1

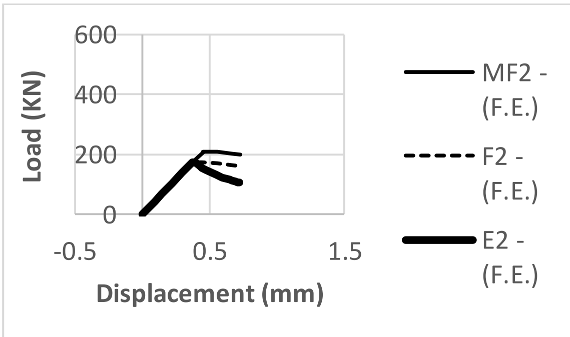

Fig.18: Numerical load-displacement for specimens E2, F2 and MF2.

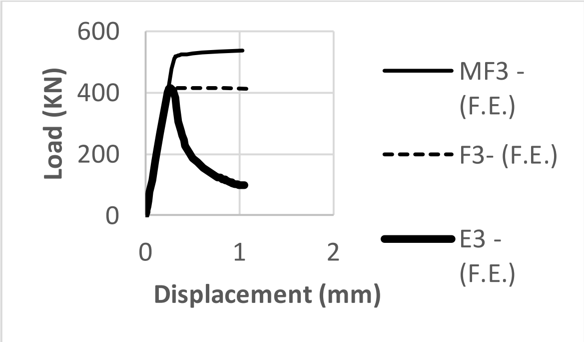

Fig.19: Numerical load-displacement for specimens E3, F3 and MF3.

5. CONCLUSIONS

The current study presented the experimental test results of a group of tests conducted on columns filled with foam to monitor the changes in their behavior and load capacity of such columns. The study also included an extensive parametric study using finite element for the parameter of using metallic foam inside circular columns using ABAQUS. The following conclusions can be summarized from the current study:

1) The load carrying capacity of steel tube columns was not increased by filling it with spray foam which had relatively low density of 30 *kg/m*^{3}.
2) The ductility in load-displacement was increased by filling steel columns with spray foam which had relatively low density of *30 kg/m*^{3}.
3) The load carrying capacity of steel tube columns was increased by filling it with metallic foam (structural foam) with high density of 810 *kg/m*^{3}.

6. REFERENCES

[1] Thornton, P.H., "Energy Absorption by Foam Filled Structures", SAE Technical Paper Series 800081, 1980.

[2] Reid, S.R., Reddy, T.Y., and Gray, M.D., "Static and Dynamic Axial Crushing of Foam- Filled Sheet Metal Tubes", International Journal of Mechanical Sciences, 28, pp 295-322, 1986.

[3] Seitzberger, M., Rammerstofer, F., Degischer, H., and Gradinger, R., "Crushing of Axially Compressed Steel Tubes Filled with Aluminum Foam", Acta Mechanical, 125, pp 93-105, 1997.

[4] Seitzberger, M., Rammerstofer, F., Gradinger, R., Degischer, H., Blaimschein, M., and Walch, C., "Experimental Studies on the Quasi-Static Axial Crushing of Steel Columns Filled with Aluminum Foam", International Journal of Solids and Structures, 37, pp 4125-4147, 2000.

[5] ABAQUS Standard User's Manual, Vol. 1-3. Version 6.4. USA: Hibbitt, Karlsson and Sorensen Inc., 2004.