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EXPERIMENTAL INVESTIGATION OF VIBRATION DAMPING IN STEEL FOAM SANDWICH STRUCTURES

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Abstract
This research project is an experimental investigation on the structural dynamic properties and vibration damping of steel foam sandwich beam specimens. The sandwich specimens comprise DC01 mild steel plates and steel foam hollow spheres bonded together with a thermosetting epoxy. Specimens included single-phase steel foam core sandwich specimens and two-phase specimens with semi-filled steel foam cores with different volumes of lubricant oil. Three different tests were performed, specifically sine sweep over a range of frequencies, white noise and shock. The results show very good correlations in the estimation of the harmonic frequencies and promising damping ratios for the single-phase cores with further improvements in the presence of two-phase cores.

Introduction
Steel metal foams are a special type of porous metals that aim to merge typical metal properties of strength and ductility with low weight and energy dissipation (Banhart 2002). Steel foam comprising steel foam hollow spheres, prepared by Hollomet GmbH and coated by a thermosetting epoxy Araldite AT1-1 are bonded together to form the core of sandwich configuration surrounded by two mild steel face plates DC01. The motivation for this investigation came from the hypothesis that steel foam sandwich components can be ideally used as lightweight stiffeners against buckling that can also exhibit multi-functionality by passively attenuate vibrations in civil infrastructures such as steel bridges and wind turbine towers. This investigation was conducted on specimens (Figure 1(a)) developed during the EU FP7 Project INSIST (Yiatros, 2016), where the static compressive and shear properties of the steel foam were determined as well as their shear fatigue life. Although some studies investigating the damping coefficient of aluminium foams do exist (Banhart et al, 1996), there is a large variability of the results due to the soft nature of the material and different methods used (Goletti, et al, 2014). This work aims to define the dynamic characteristics of the composite prototype panel with 3 different test types. The aim is to quantify the damping characteristics of the single phase material over a spectrum of frequencies as well as quantify the effect of adding a viscous liquid in the steel foam core (2-phase core) and evaluating the damping ratio increase.

Mechanical properties
Two types of specimens with different lengths were used, 290D and 500D respectively. 1-phase sandwich specimens with mild steel face plates and 2-phase semi-filled cores with different lubricant oil volume. The mechanical properties are shown in Table 1. All specimens are 80mm wide and steel face plates are 2mm thick. The oil density is 0.75g/ml.

Face plate Young's modulus	210 GPa	Core elastic compressive modulus	560 MPa
Face plate Poisson ratio	0.3	Core shear modulus	267 MPa
Face plate min yield stress	280 MPa	Core Poisson ratio	0.05

Table 1 – Mechanical properties of steel sandwich components.

Experimental procedure
The dynamic characterization of the samples has been performed using an electrodynamic shaker V400HG/DSA4 of Data-Physics. The closed loop control of the shaker was provided by a Signal-Star Vibration Controller and the corresponding control software. The signal acquisition has been done using a Polytec OFV-505 laser vibrometer to measure the output on

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the tip of the specimen and using a PCB piezoelectric accelerometer to measure the shaker feedback signal. Figure 1(b) the setup.

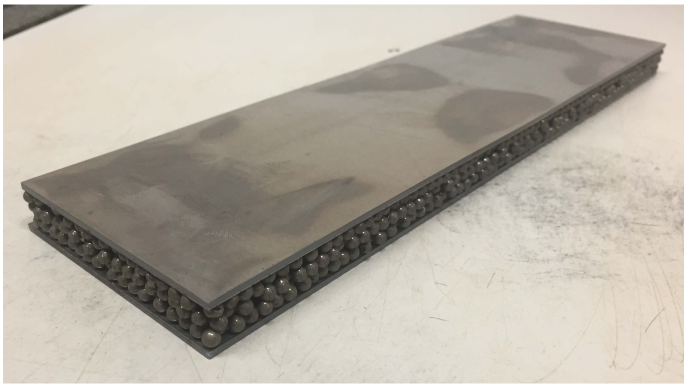


Figure 1 (a) – A SFS4 specimen. (b) – Experimental set up for vibration testing.

Concerning the type of tests carried out on each specimen, three procedures have been defined using different excitations: a sweep sine, a random noise and an impact (Table 2).

Specimen code	Length [mm]	Oil volume in core [ml]	Sweep sine	Random noise	Impact
SFS4-500D-I	500	60	30-500 Hz	0.0025 g/√Hz	20 g
SFS4-500D-II	500	60	30-500 Hz	0.0025 g/√Hz	20 g
SFS4-500D-III	500	0	30-500 Hz	0.0025 g/√Hz	20 g
SFS4-500D-IV	500	0	30-500 Hz	0.0025 g/√Hz	20 g
SFS4-290D-I	290	20	n/a	0.0025 g/√Hz	20 g
SFS4-290D-II	290	0	n/a	0.0025 g/√Hz	20 g
SFS4-290D-III	290	0	n/a	0.0025 g/√Hz	20 g
SFS4-290D-VI	290	40	n/a	0.0025 g/√Hz	20 g
SFS4-290D-VII	290	40	n/a	0.0025 g/√Hz	20 g

Table 2 – Specimen characteristics and tests. Cantilever spans for 500D specimens is 235mm and 240mm for the 290D specimens.

In all the three different tests, it was possible to record both the input and the output signals, thus allowing for input-output identification methods. The 500D specimens were in a double cantilever configuration (235mm cantilever span on either side) and the 290D specimens in a single cantilever configuration (240mm cantilever span). The laser vibrometer target was located at 20mm from the free end of the cantilevers. The ***sine sweep*** was only performed on the symmetric 500mm-long specimens to minimize shaker interference. An open loop control strategy was pursued, setting two acceleration levels at 30Hz (0.5g and 2g) and then carrying out the test with constant driving voltage, targeting for the 1st harmonic. ***Random noise testing*** bandwidth between 30 to 2000Hz were selected for the 500mm specimens and 30 to 2500Hz for the 290mm. Low frequencies (under 30Hz) were eliminated to avoid shaker interference since no relevant modes were present at that area. The root mean square amplitude of the random noise was set to 0.025g/√Hz. Finally the ***shaker impact testing*** procedure was defined with a trial and error approach. The final parameters selected were a half-sine impact profile, with a time length of 3 ms and a peak-amplitude of 20g. The laser vibrometer thus recorded a free-decay response of the specimen to this impact. The feedback accelerometer recorded the input signal. For all the tests the acquisition setup has been the same: a National Instrument data acquisition NI-9234 module has been used and the signals were acquired using a standard Lab View software at a sampling frequency of 10240 Hz.

Analysis

In order to estimate a modal model, the Rational Fractional Polynomial method has been used in order to fit the FRF of the model in the range 0-2000 Hz for 500 mm samples and 0-2500 Hz for 290 mm samples (in order to excite the third mode also for short samples). A suited order of the model has been selected for each specimen (usually in the range 3-5) in order to fit also numerical spikes in the FRF. The results are listed in Tables 3-5 and shown in Figure 2.

	1st Harmonic [Hz] (0.5g)	Damping [%]	1st Harmonic [Hz] (2g)	Damping [%]
SFS4-500D-I (60ml)	233.59	1.56	229.50	2.38*
SFS4-500D-II (60ml)	239.10	0.90	239.71	1.31
SFS4-500D-III	230.57	1.61	230.52	0.48
SFS4-500D-IV	241.27	0.79	242.73	1.45

Table 3 – Sine sweep 30-500Hz. Asterisk in some first harmonic damping factors indicates overestimation because of double peak resonance (underfitting of the rational fractional polynomial method).

	Freq [Hz]	Damping [%]	Freq [Hz]	Damping [%]	Freq [Hz]	Damping [%]
SFS4-500D-I (60ml)	227.70	0.59	793.90	0.53	1654.20	0.11
SFS4-500D-II (60ml)	243.60	0.42	871.90	0.55	1833.30	0.71
SFS4-500D-III	231.80	0.68	808.50	0.34	1612.90	0.40
SFS4-500D-IV	248.70	0.86	838.60	0.25	1795.20	0.78
	Freq [Hz]	**Damping [%]**	**Freq [Hz]**	**Damping [%]**	**Freq [Hz]**	**Damping [%]**
SFS4-290D-I (20ml)	190.60	4.04*	956.10	0.37	1961.20	0.62
SFS4-290D-II	250.90	1.67	1039.10	0.21	2158.30	0.10
SFS4-290D-III	193.40	0.71	955.20	0.16	1927.50	0.26
SFS4-290D-VI (40ml)	193.70	5.88*	870.40	0.35	1768.40	1.16
SFS4-290D-VII (40ml)	156.20	2.54	902.00	0.31	1681.90	0.20

Table 4 – White noise results (rms 0.0025 g/√Hz). The real modal damping can be safely assumed to be roughly half the listed value.

	Freq [Hz]	Damping [%]	Freq [Hz]	Damping [%]
SFS4-500D-I (60ml)	230.17	1.19	791.16	0.62
SFS4-500D-II (60ml)	246.70	0.87	842.10	1.35
SFS4-500D-III	236.60	1.23	794.80	2.35
SFS4-500D-IV	226.30	1.39	807.30	1.51
	Freq [Hz]	**Damping [%]**	**Freq [Hz]**	**Damping [%]**
SFS4-290D-I (20ml)	198.67	5.13	957.20	0.40
SFS4-290D-II	242.90	2.01	1039.20	0.28
SFS4-290D-III	180.90	2.61	960.10	1.49
SFS4-290D-VI (40ml)	198.80	2.14	871.10	0.41
SFS4-290D-VII (40ml)	150.90	2.30	893.30	0.46

Table 5 – Shock test

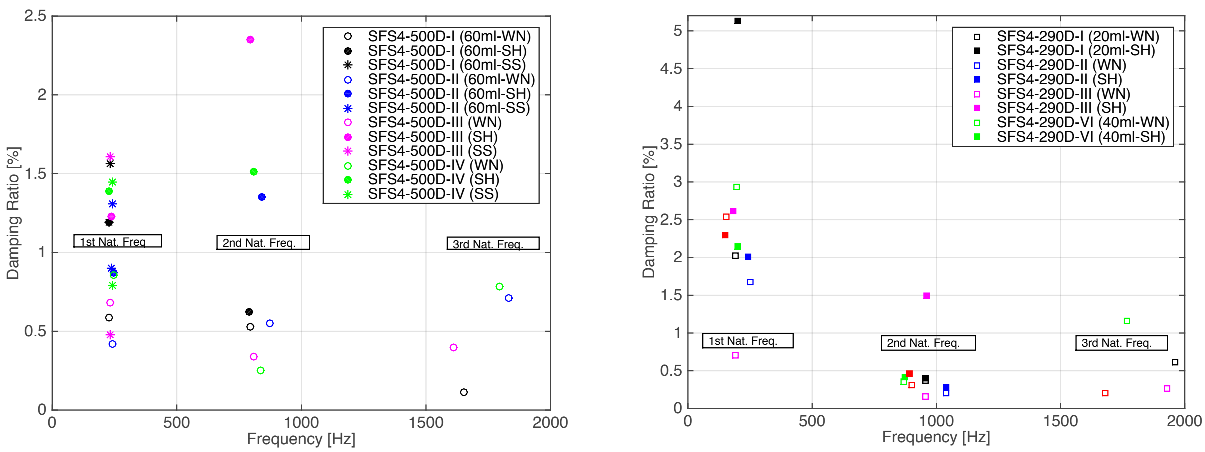

Figure 2 – Damping ratio [%] Vs Frequency [Hz] for all tests. Left: 500D specimens (235mm span), Right: 290D specimens (240mm span). WN denotes white noise test, SH denotes shock test and SS denotes sine sweep.

Discussion

The experimental results for the double cantilever specimens (500D) exhibit an excellent correlation with analytical results (3-4% difference) for the first harmonic in all three tests, while the 290D specimens the difference was in the range of 10-15%. The increased percentage difference is attributed to the asymmetry of the setup (i.e shaker interference), while the variability between specimens is attributed to material and geometric imperfections.

Comparing the results between each method, it seems that the shock results show lower variability in the damping ratios estimations, especially for the first natural frequency. All three methods show a visible decay in damping ratios at increasing frequencies. When considering the 2-phase cores (i.e. presence of oil in the core), the white noise test did not seem to show any differences between the specimens, especially for the 500D configuration. On average, the damping ratio for the single-phase cores at the first natural frequency was 1.06% and 1.75% for the 500D and 290D specimens respectively. The presence of the two-phase cores brought an increase between 91-175% for the 290D specimens, where there was virtually no difference in the 500D specimens, probably due to the underestimation of any increases in the white noise and sine sweep tests.

Conclusion

This was a short experimental investigation to evaluate the potential of lightweight steel foam sandwich prototypes to act as passive dampers in flexural vibration. Three different procedures were used to test steel foam sandwich beams with single and double phase cores. In any case the damping ratios for the first natural frequencies in all instances are higher by at least five times those of solid steel (0.1-0.2%) (Bachmann et al, 1995) as well as more than double ratios compared to the results of aluminium foam tests (Banhart et al, 1996; Golleti et al, 2014) owing probably to the less variability of the material and the composite action of the epoxy resin in steel foam cores, indicating a promising potential of the material as a passive damper. The presence of the 2nd phase (i.e. volume of oil in the core) had mixed responses, which were also specific to each test. The results are indeed positive and we will be looking to develop these prototypes further, such using quartz sand to infiltrate pores and finding the best ratio of infill materials used for tuning vibration damping.

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