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SIMULATION OF IMPULSIVE LOADING ON COLUMNS USING AN INFLATABLE AIRBAG TECHNIQUE

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Abstract

The purpose of this study was to simulate impulsive loading on columns by an innovative lab-based experimental technique that utilises inflatable airbags. Mild and stainless steel hollow section columns with effective lengths of 955mm and under simply supported condition were used in this study. The effect of filling the columns with sand infill as a shock absorbing material was also investigated. A custom-made airbag mounted between the steel column specimens and an impact surface was subjected to an impact of a 590kg falling mass. Each specimen was tested under two impact velocities of the falling mass. Upon impact, the pulse pressure generated in the airbag was transferred uniformly to the steel columns through a plywood panel. The air pressure, mid-span displacements and strains were measured by using a high-speed data acquisition system. From the experimental results, it was observed that the load duration was relatively long compared to the fundamental period of vibration of the columns which resulted in a quasi-static regime of response of the steel columns. The proposed technique could be relevant for studying the response of structural elements subjected to the effects of far-field explosions, as may be experienced in the petrochemical and mining industries.

Keywords: Impulsive loading, column, airbag, quasi-static response, blast simulator, sand infill

1. Introduction

The responses of structures under blast loading are commonly investigated by testing the structures using high explosives in the open arena or using shock tube testing. Open arena high explosives testing can be performed on a full scale specimen or scaled down model. The advantages of this method include the ability to test many specimens simultaneously and the ability to replicate the actual condition under detonation of high explosives. High-speed camera footage can be captured easily and is valuable as a scientific data acquisition system. The problems with this method are that it is generally quite expensive compared with other methods and there are difficulties in data acquisition and a long planning time is needed.

The shock tube is a device used for the study of gas phase combustion reactions and aerodynamic flow under a range of pressures and temperatures that cannot be replicated easily in other testing facilities. Shock tube testing involves mounting the test specimen at the end of a large tube in a laboratory. The shock tube consists of both a low and high pressure gas that are separated by a diaphragm. Testing is initiated by bursting the diaphragm where high pressure gas known as ‘ driver gas’ travels toward the low pressure gas known as ‘ driven gas’. A compression wave strikes the driven gas, which forms a pressure pulse or shock front. The pressure pulse is generated in one end of the shock tube, which travels toward and impacts with the test specimen.

Shock tube testing is generally less expensive than open arena high explosives testing, loads are more reproducible and the tests can be conducted reasonably quickly. The difficulties with this testing are that only one specimen can be tested at a time and the specimen size is limited by the size of the shock tube.

Gram et al [1] developed a laboratory simulator of blast loading on building and bridge structures. The system uses impact loading to produce a 2ms pulse with a typical peak pressure loading of 35MPa and an impulse of 14kPa-s over the surface of the column. The system comprises a blast generator and an impacting mass. The blast generator has a hydraulic actuator that can produce a maximum force of about 250kN to accelerate the impacting mass. The impacting mass is a steel plate bolted to the end of the piston. An elastomer spring is mounted on the steel plate to reduce excitation of high frequency vibrations in the impacting mass and the specimen.

A blast load simulation system for the testing of glazing has been proposed by Mostaghel [2]. The testing system aims to provide a method for simulation of loading that can be used as a standardized test for research into the capacity of glazing as well as other panels to resist blast loading. The invention comprises a test panel of glazing and a membrane mounted within a frame system as illustrated in Figure 1. The membrane in conjunction with the frame system covers one or more surfaces of the glass panel to form an airtight chamber. The airtight chamber is inflated with a fluid medium such as air before testing.

The impulse delivery system comprises a plate of known weight that is dropped onto the membrane at various heights to achieve the required impulse magnitude and duration. The plate is mounted to a linear guide which has one end secured to a frame structure. By changing the mass and drop height of the plate, impulses of desired magnitudes can be obtained. The impulse duration can be selected by changing the drop height and the initial pressure under the membrane.

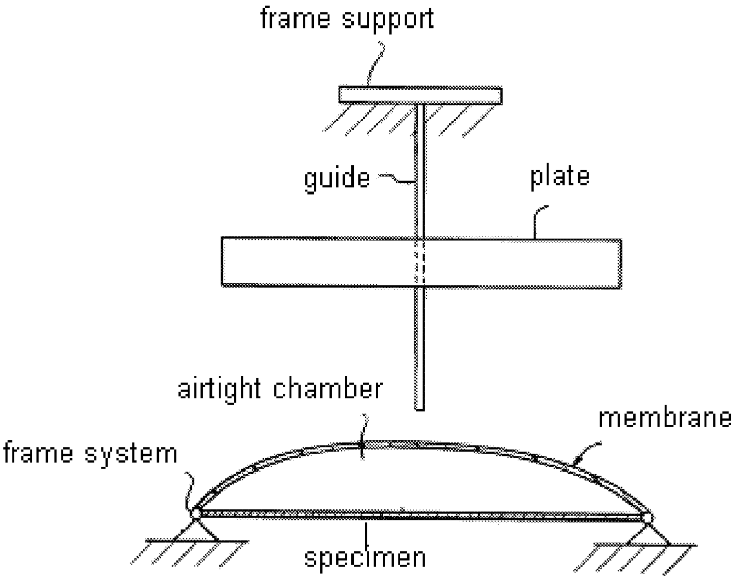


Figure 1: Experimental setup for blast load simulation system for glazing. [2]

The abovementioned experimental techniques such as open arena high explosives testing, shock tube and laboratory blast simulator are either expensive or require sophisticated mechanical systems. The blast simulation system by Mostaghel [2] is relatively simple in its experimental setup, however it is not applicable for testing columns. Therefore, the aim of this study was to attempt to simulate blast loading on columns by an innovative lab-based experimental technique that uses inflatable airbags and a drop hammer to deliver an impulse. The experimental technique adopted in this study is based on the experimental technique presented by Remennikov [3] for testing glazing panel under monotonically increasing uniform pressure as shown in Figure 2, with necessary modifications.

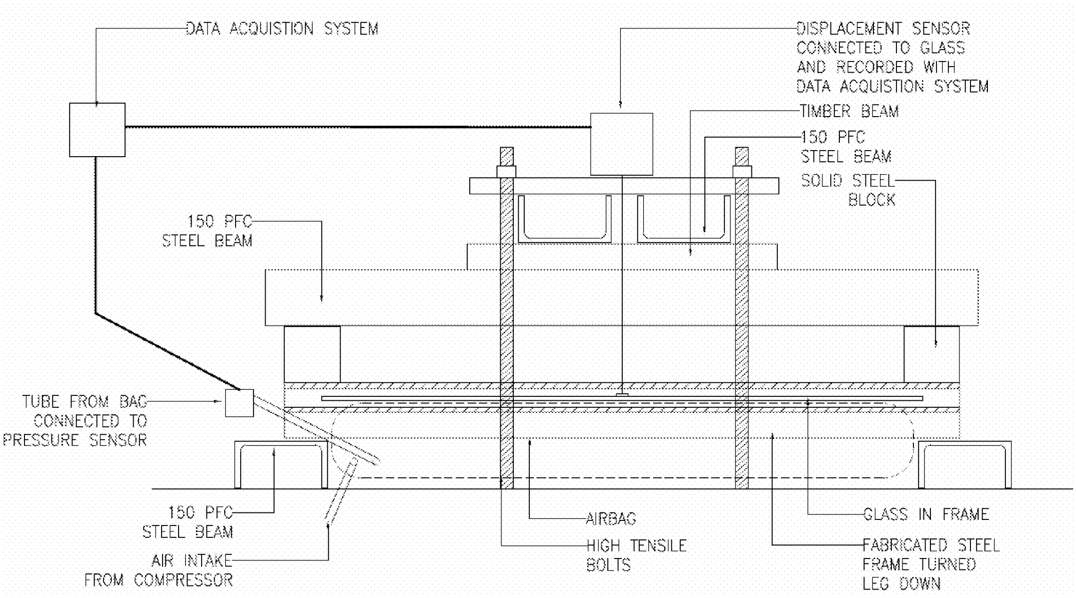


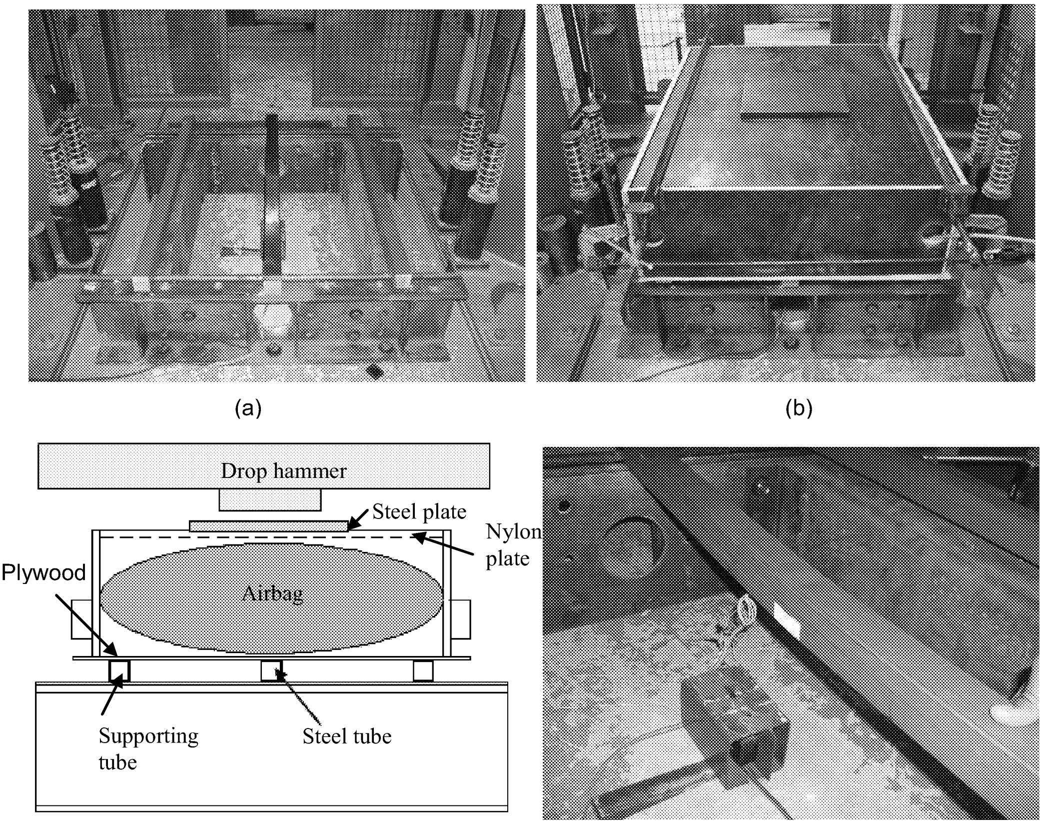
Figure 2: Experimental set-up for monotonically increased pressure on glass specimens. [3]

2. Experimental setup and instrumentation

Mild steel and stainless steel tubes with 50x50x1.5mm cross section and 1075mm length were prepared. Three types of specimen were prepared: 1) hollow stainless tube, 2) mild steel tube filled with sand, 3) stainless steel tube filled with sand. Each specimen was positioned at the middle of the supporting frame which was bolted to the strong floor as shown in Figure 3(a). The ends of the tube were sitting on top of round bars welded to the supporting frame with 955mm spacing to replicate simply-supported conditions. Two sand-filled mild steel tubes with the same dimensions were positioned on the edges of the supporting frame to support 18mm plywood mounted on top of the specimen. The plywood would distribute the airbag pulse pressure into the specimen.

The airbag was placed on top of the plywood and confined along the sides by a specially constructed plywood box. The airbag was made of durable PVC with a maximum pressure rating of 100kPa. The airbag was inflated with initial pressure. A thick, rigid nylon plate was placed on top of the airbag to provide vertical confinement to the airbag and transfer the impact load into the airbag. After that, a steel plate was mounted on the nylon plate to distribute the drop hammer impact into the nylon plate. The plywood box was clamped to the supporting frame in order to prevent the movement of the airbag during the tests as illustrated in Figure 3(b).

The drop hammer was released from the predetermined heights to impact the nylon plate, Figure 3(c), and generate a pressure pulse. The pulse pressure generated in the airbag was recorded by a pressure sensor. The mid-span displacement of the tube was measured by a high-speed displacement laser sensor placed underneath the tube, Figure 3(d). Strain gauges were attached near the mid-span to record the deformation history. All the instruments were connected to National Instrument high-speed data acquisition system with a 100kHz sampling rate.



(a) (b)

(c) (d)

Figure 3: (a) Plan view of steel tubes positioned on top of the supporting frame; (b) complete setup of the test with the airbag confined in the plywood box; (c) cross section view of each component in the test ; (d) deformation of the tube after Test 2.

3. Experimental program

The experiment program is summarized in Table 1. The mild steel RHS with sand-infill was subjected to the impact of a drop hammer released from 50mm to investigate the elastic response of the specimen. The same specimen was then subjected to the impact from a drop hammer at 500mm drop height to obtain its plastic response. The stainless steel RHS with sand in-fill was subjected to the same drop heights of 50 and 500mm. Finally a stainless steel RHS was subjected to the impact from a drop hammer from a 500mm drop height.

Table 1: Experiment program

Test	Specimen	Drop height (mm)
1	Mild steel RHS with sand in-filled core	50
2		500
3	Stainless steel RHS with sand in-filled core	50
4		500
5	Stainless steel RHS	500

4. Experimental results and observations

Experimental data recorded from each test included: 1) the airbag pressure histories, 2) mid-span displacement histories and 3) deformation histories at the mid-span of the specimen. Results from Test 1 are shown in Figure 4. It can be seen that the load duration on the tube was about 200ms and the peak pressure attained was 28kPa. The peak mid-span displacement was 5mm while the maximum strain was 1400 $\mu\varepsilon$. Under this loading, elastic response of the tube was confirmed by the displacement and strain reading returning to zero after the first impact. It was observed during the test, that the drop hammer rebounded and impacted the thick steel plate for the second time after the first impact. The pressure, displacement and strain history records for the second impact are not discussed in this paper.

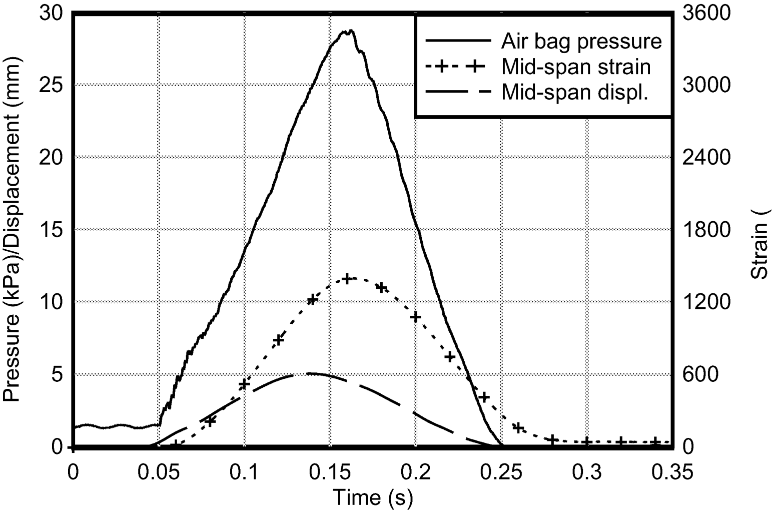


Figure 4: Experiment results of Test 1 (sand-filled mild steel RHS under an impact of 50mm drop height).

The results of Test 2 presented in Figure 5 show that the load duration was slightly shorter than that for Test 1, being approximately 150ms. The loading history has a trapezoidal shape compared to the triangle shape in Test 1 with the maximum pressure recorded of 46kPa. The maximum mid-span displacement was 33mm and the residual displacement was 21.5mm. The strain gauge failed at 4200$\mu\varepsilon$ during the test thus the actual maximum strain could not be obtained. The specimen showed a flexural failure mode with local buckling on the top flange as shown in Figure 3(d).

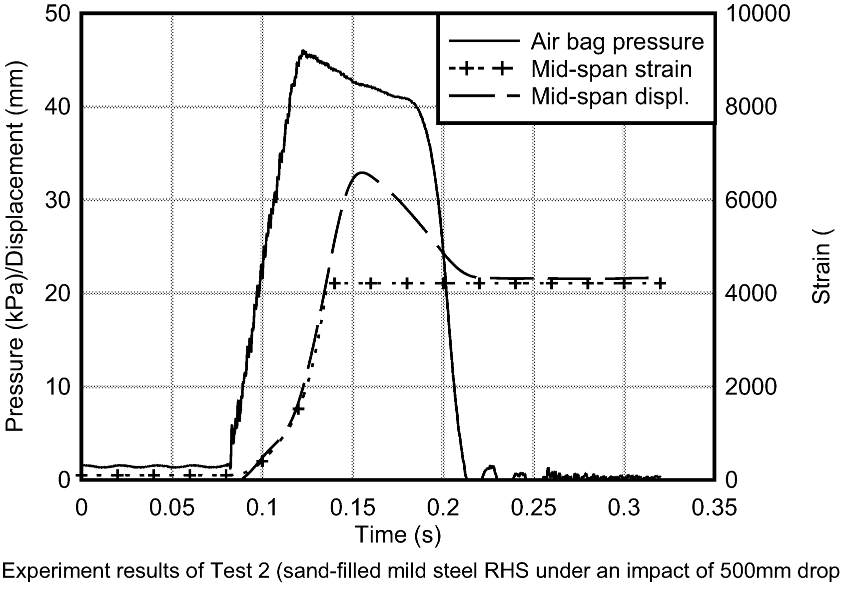


Figure 5: Experiment results of Test 2 (sand-filled mild steel RHS under an impact of 500mm drop height).

The airbag pressure recorded in Test 3 is abnormal with the recorded maximum pressure of only 8.8kPa as shown in Figure 6. The reason for the error is unknown and there was no noticeable leak in the airbag. The pressure in this test was expected to be similar to that in Test 1 in terms of the magnitude and loading history shape since the drop height was the same. The maximum displacement was 4.1mm and the maximum strain was approximately 1100 $\mu\varepsilon$. There was no residual displacement and strain in the specimen after first impact.

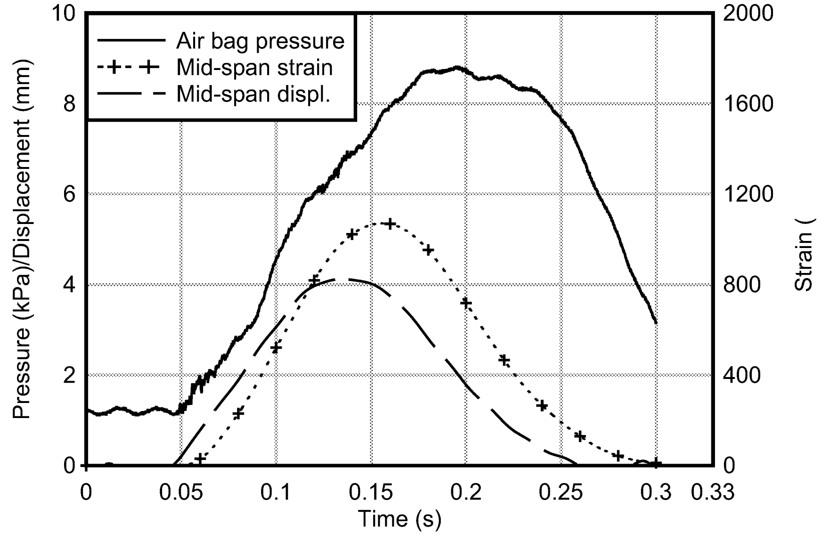


Figure 6: Experiment results of Test 3 (sand-filled stainless steel RHS under an impact of 50mm drop height).

Analysis of the results of Test 4 shown in Figure 7 demonstrated that the pressure record was erroneous. The reason for the error was found to be the leakage of the airbag during the test. The loading history has a trapezoidal shape and high-frequency oscillations were recorded at the initial stage of the impact. By ignoring these oscillations, the maximum pressure recorded was approximately 7kPa. Even though the recorded pressure is lower than in Test 3, the magnitude of deformations was higher. The maximum mid-span displacement and strain were 9mm and 2350 $\mu\varepsilon$, respectively. The specimen deflected slightly with a residual mid-span displacement and strain of 2 mm and 400 $\mu\varepsilon$, respectively after the test.

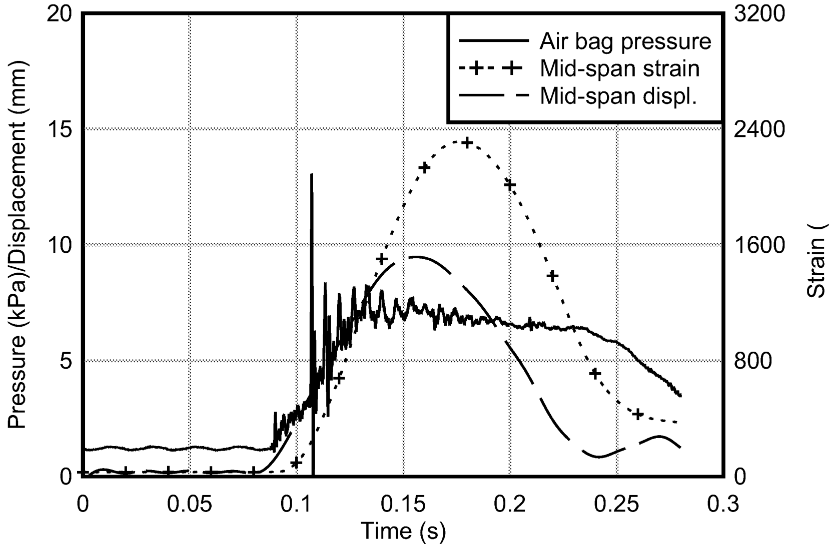


Figure 7: Experiment results of Test 4 (sand-filled stainless steel RHS under an impact of 500mm drop height).

The pressure history of Test 5 had a sinusoidal shape with a maximum pressure of 68kPa as shown in Figure 8, compared to 46kPa in Test 2. The load duration was 130ms which is similar to that of Test 2. The maximum mid-span displacement and strain were 11mm and 3000 $\mu\varepsilon$, respectively. The specimen yielded with a residual displacement of about 2mm and a residual strain of 700 $\mu\varepsilon$. It was observed that both Test 4 and Test 5 recorded similar mid-span displacement and strain histories even though the pressure history in Test 4 was erroneous.

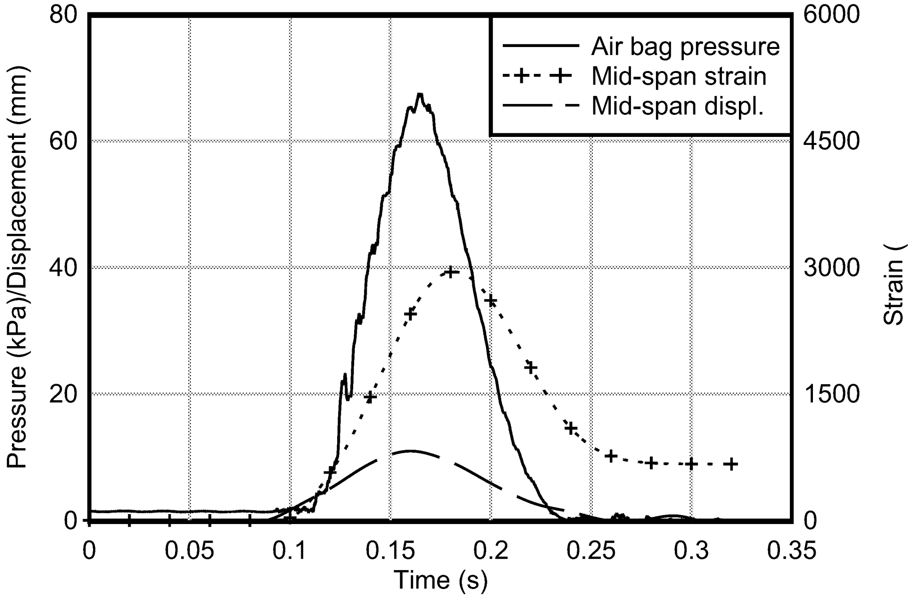


Figure 8: Experiment results of Test 5 (stainless steel RHS under an impact of 500mm drop height).

5. Determination of the loading regime

Mechanical properties for sand and steel tubes required to determine the response regime of the tubes are given in Table 2 and Table 3, respectively. The loading response is determined in Table 4. It should be noted that only Test 1, 2 and 5 are included in the determination of response regime since Test 3 and 4 gave erroneous pressure histories. From Table 4, it was concluded that the tubes are under quasi-static loading response since ωt_d is more than 40 [4], where ω is the natural circular frequency and t_d is the load duration.

Table 2: Properties of sand

	Sand
Density (kg/m^3)	**1588**
Young modulus (MPa)	24
Mass of infill (kg)	3.77

Table 3: Properties of steel tubes

	Mild steel hollow section	Stainless steel hollow section
Density (kg/m^3)	7800	8000
Young modulus (GPa)	200	200
Cross-sectional area (mm^2)	291	291
Mass of hollow section (kg)	2.44	2.50
Moment of inertia, I (mm^4)	114193	114193

Table 4: Calculation of response regime

	Sand-filled mild steel tube		Hollow stainless steel (Test 5)
	Test 1	Test 2	
Total mass, m (kg)	6.21	6.21	2.50
Total stiffness, K (kN/m)	1412	1412	1412
Load duration, t_d (s)	0.25	0.14	0.11
Load mass transformation factor, K_{LM}	0.78 (elastic)	0.66 (plastic)	0.66 (plastic)
$\omega = (K/K_{LM}m)^{1/2}$	540	587	925
ωt_d	135	82	102
Response regime	Quasi-static	Quasi-static	Quasi-static

6. Conclusion and future work

The use of airbags in combination with the drop-weight impact testing technique is a viable approach for simulation of loads due to far-field explosions. Based on the test results presented in this paper, a load duration between 100ms and 200ms can be achieved. However, the pressure histories of the airbag in Test 3 and 4 are erroneous. For Test 3 the reason for the error is unknown while in Test 4 the leakage of the airbag caused the error. The effect of sand-infill on the column response and comparison between mild steel and stainless steel columns can not be properly evaluated in this study due to these errors.

The complete experimental setup should be modelled using a nonlinear finite element explicit code and calibrated against experiment results of Test 1, 2 and 5. With such a calibrated model, Test 2 and 3 should be simulated and numerical results can then be used to investigate the effects of sand-infill and allow a comparison between mild steel and stainless steel to be drawn. The application of an airbag in the impulsive loading regime should be further investigated in FE software. The initial airbag pressure and height of drop hammer should be adjusted to shorten the load duration as discussed in [2].

7. Acknowledgements

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