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Comparative Analysis of Aluminum Alloy 6061-T6 and Mild Steel Tubes in Sacrificial Protection System under Blast Loading

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Abstract

A sacrificial cladding consist of hollow metal tubes and steel sheet, is proposed in this study to protect a square concrete panel subjected to blast loading. Herein, comparative analysis of aluminum alloy 6061-T6 (Al 6061-T6) and mild steel tubes in sacrificial cladding is done using 3-D non-linear Finite Element (FE) software ABAQUS/Explicit®. Blast load is applied through ConWep program developed by US Army. Simplified Concrete Damage Plasticity (SCDP) model is used to define the material behavior of concrete slabs of thickness 250 mm. Johnson-Cook (J-C) plasticity model is used to model the stress-strain response of Al 6061-T6 and mild steel tubes, reinforcement bars and steel sheet. Diameter (*D*) and thickness (*t*) of circular metal hollow tubes are taken from IS1161:1998. Comparative analysis of Al 6061-T6 and mild steel tubes is carried out for blast loading using TNT with scaled distance of 0.425 m/kg$^{1/3}$. It was observed that mild steel tubes perform better than Al 6061-T6 tubes and save concrete panel from degradation under blast loading.

Keywords: Blast Loading, FE Analysis, ConWep, J-C Model, Sacrificial Tubes, Simplified Concrete Damage Plasticity

1. Introduction

The protection of civilian population in case of blast attacks is very comprehensive and complex task. Many solutions have been proposed for protection of civil structures subjected to explosions [1-2]. Goel et al. [3] used stiffeners to increase the resistance of steel plate subjected to blast loading. Among most of proposed solutions, the use of sacrificial cladding gains more attraction as per their predictable behavior and functions [4]. In sacrificial cladding, two or more layers can be used based on the properties and strength of materials. Outer layer is mainly used to distribute pressure uniformly on inner layers or core. The core then deforms progressively and minimizes the transfer of force to main structure. Further, materials with low failure loads are used in inner layers or core in order to achieve plastic deformation during an explosion.

Herein, a sacrificial cladding is analyzed for blast loading using non-linear 3-D finite element software ABAQUS/Explicit® [5]. Two types of sacrificial cladding (SC1 and SC2) are modeled in this study for protection of concrete panel subjected to blast loading. Material properties of mild steel are used for tubes in SC1, whereas material properties of aluminum alloy 6061-T6 (Al 6061-T6) are used for tubes in SC2. The main objective of present study is to compare the performance of sacrificial cladding under blast loading with tubes made of two different metals. Numerical simulation is done for sacrificial cladding with Al 6061-T6 alloy and mild steel tubes. The outer diameter and thickness of hollow tubes are considered as per IS1161:1998 [6]. The thickness of tubes is 2.9 mm for both the cases. Table 1 shows the cases considered in the present study.

2. Finite Element Modeling

Herein, square concrete panel of dimension 1250 mm have been modeled with 250 mm thicknesses (ts) using M40 grade of concrete (maximum compressive strength of 40 MPa). Reinforcement bars of tensile yield strength 250 MPa and diameter 12 mm are embedded in concrete panel. These bars are provided on top and bottom side of concrete panel with clear cover and spacing of 30 mm and 75 mm, respectively. Sacrificial cladding consists of hollow metal tubes along with 3 mm thick steel sheet to protect the concrete panel from blast loading with scaled distance of 0.425 m/kg1/3. In order to develop the sacrificial system, tubes are first welded to front steel plate and then welded to bottom circular steel plates of 3 mm thickness. These small circular steel plates are placed at spacing of 250 mm center to center. Then while attaching this sacrificial system on concrete surface, these small circular plates will be attached to concrete surface using pre-inserted bolts in the concrete. Thus, each panel of sacrificial system is attached and tightened manually using the nut and bolt connection. The distance between the edge of slab and center of corner tubes is 125 mm. Total 25 tubes are used as sacrificial system with three different lengths 125 mm, 150 mm and 175 mm. Further, in the present analysis, perfect connections between

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Table - 1. Cases considered in the present study.

Nomenclature	Metal used in Tubes	Thickness of Tubes (mm)	Outer Diameter of Tubes (mm)	Length of Tubes (cm)	Weight of Sacrificial Cladding (kg)
SC1	Mild Steel	2.9	60.30	12.5	49.74
				15.0	52.31
				17.5	54.88
SC2	Al 6061-T6	2.9	60.30	12.5	41.33
				15.0	42.21
				17.5	43.10

all the components are assumed and hence, bolts are not modeled explicitly in this study. Fig. 1 (a) to Fig. 1(e) shows the geometries of parts modeled along with connection detail of sacrificial layer with the concrete in present study.

ConWep program developed by US army is used to apply blast loading on the surface of concrete slab and steel plate [7]. Fixed boundary conditions are used for concrete slab to restrain the movement of concrete slab during blast loading. Steel sheet with dimension more than concrete slab should be used to protect the sides of concrete slab from blast pressure. To reduce the computational cost steel sheet of equal dimension to concrete slab is modeled with symmetric boundary conditions in X and Z directions. Interaction properties using general contact with hard normal behavior and tangential behavior with penalty of 0.55 between steel and concrete is used in present study. Further, the value of 0.2 is provided for sliding coefficient of friction between different metal parts.

3. Material Models

3.1 Material Model for Concrete

Isotropic tensile and compressive plasticity's are used in concrete damage plasticity model to study the behavior of concrete in non-linear manner. The value of strain (ε) comprises of elastic strain (ε^{el}) and plastic strain (ε^{pl}) and yielding of surface is controlled by two hardening variables of failure mechanism of concrete under compression and tension. In this study, simplified concrete damage plasticity (SCDP) model is used. For confined and unconfined concrete, there is parabolic increase trend in hardening stage of concrete and a linear trend in softening stage. In SCDP, the whole model considered as non-linear parabolic curve and constitutive model only comes into effect after stress reaches 60% of concrete`s compressive strength and the value of stress in softening stage is not allowed to decrease below 20% of unconfined cylinder compressive strength. Material properties of concrete as per SCDP are shown in Table 2. The value of damage parameters considered in this study is taken from [8]. Fig. 2 shows the stress-strain response of concrete under compression and tension used in this study.

3.2 Material Models for Steel and Al 6061-T6

Herein, mild steel and Al 6061-T6 alloy for hollow tubes, sheets and reinforcement is modeled using Johnson-Cook (J-C) plasticity model. This model is commonly used for high strain rate deformation of metallic materials. Stress-strain response of materials in J-C model is defined by equation:

$$\sigma = \left(A + B\varepsilon^{n}\right)\left(1 + C\dot{\varepsilon}^{*}\right)\left(1 - T^{m}\right) \tag{1}$$

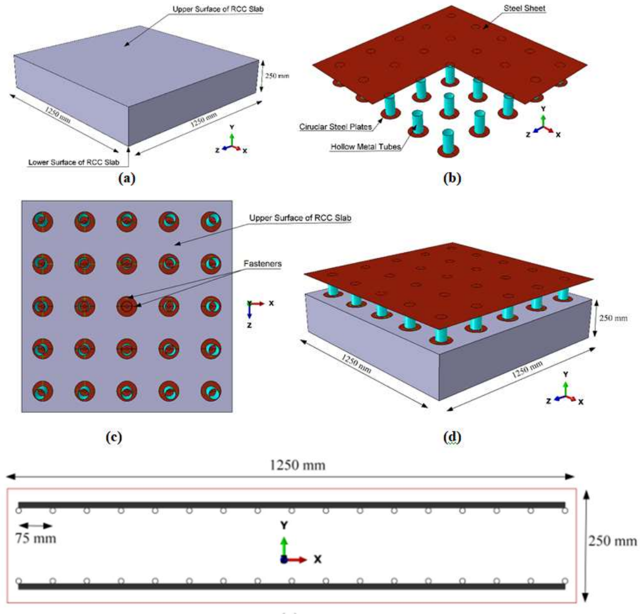

Fig. 1. (a) Three-dimensional view of concrete panel with upper and lower surfaces, typical exploded view of the sacrificial layer considered, (c and d) connection details of sacrificial layer with upper surface of concrete, (e) position of reinforcement bars along with spacing.

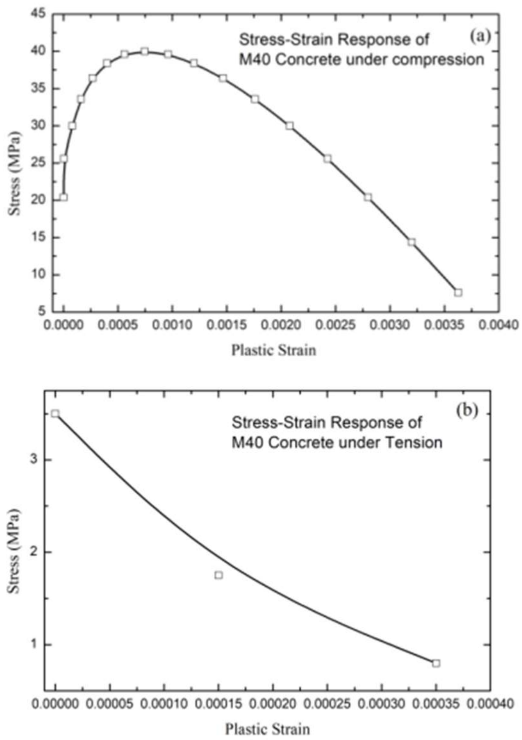

Fig. 2. Stress vs plastic strain curve for M40 concrete under (a) compression and (b) tension considered in the present study [8].

Table - 2. Material properties of concrete used in present study [8].

E (GPa)	Poisson's Ratio, μ	Density, ρ (kg/m^3)	f_{cu} (N/mm^2)	f_{ct} (N/mm^2)
30	0.2	2400	40	4

Here, A is the yield stress on 0.2% offset strain; B, C, m and n are the material constant represent strain hardening of material. $\dot{\varepsilon}^*$ is dimension less plastic strain; $\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0$, where $\dot{\varepsilon}$ is equivalent plastic strain rate and $\dot{\varepsilon}_0$ is the reference strain rate whose value is taken as 1/s for mild steel and steel; ε is equivalent plastic strain; T is homologues temperature. Temperature based hardening is not considered in present study. Tubes are modeled using J-C plasticity model parameters whose values are measured by Split-Hopkinson pressure bar (SHPB) technique with strain rate ranges between 10 s^{-1} to 1800 s^{-1} for mild steel, and 1300 s^{-1} and 4300 s^{-1} for aluminum. For steel sheet, reinforcement bars and curved circular plate, modulus of elasticity, E = 210 GPa, tensile yield strength of 250 MPa, density = 7875.81 kg/m^3 and Poisson ratio equals to 0.3 have been considered whereas for mild steel tubes, density equals to 7850 kg/m^3 and tensile yield strength of 200 MPa have been considered and rest material parameters are same as that of steel sheet and reinforcement. Density, tensile yield strength, modulus of elasticity and Poisson ratio for aluminum 6061-T6 considered in this study are 2700 kg/m^3, 275 MPa, 69 GPa and 0.33, respectively. The material constants used herein for J-C plasticity model of steel sheet, plate and reinforcement are A = 360 MPa, B = 635 MPa, C = 0.075, n = 0.114 for strain rate of 100/s [9]. For mild steel tubes the material constants are A = 217 MPa, B = 233.7 MPa, c = 0.0756, n = 0.6428 for strain rate ranges between 10/s to 1800/s [10]. Material parameters for J-C plasticity model of Al 6061-T6 are A = 340 MPa, B = 1018 MPa, C = 0.0568, n = 0.7789 for strain rate ranges between 1300 /s to 4300 /s with reference strain rate of 0.0001 /s [11].

3.2 Blast Loading

Blast loading is applied on the top surface of concrete panel through ConWep program. The charge is at a stand-off distance of 1 m and scaled distance of blast is 0.425 m/kg$^{1/3}$. The blast load is computed using Eq. 2 as [7],

$$P(t) = P_r \cos^2\theta + P_i(1 + \cos^2\theta - 2\cos\theta) \qquad (2)$$

Where, θ is angle of incidence which is defined by tangent to the blast wave front and target surface; P_r is the reflected pressure; P_i is the incident pressure. Eq. 2 can be used for free air spherical charge as well as ground surface hemisphere charge. To calculate the blast pressure ConWep program uses following inputs: (i) equivalent weight of TNT explosive, (ii) spatial coordinates of detonation point, (iii) type of blast wave (spherical or hemispherical). The actual impulse corresponding to charge weight is calculated using ConWep program and applied to the structure considering its position. An automatic time increment estimator with global stable time increment without any time scaling factor is used in this analysis.

4. Simulation Results and Discussion

A sacrificial cladding consists of hollow metal tubes and steel sheet is analyzed to protect concrete panel under explosion using Finite Element software ABAQUS/Explicit® [5]. Dimensions of circular hollow metal tubes are considered as per IS1161:1998 [6]. Sacrificial cladding is used to protect a square concrete panel with dimension 1250 mm and thickness 250 mm. Performance of Al 6061-T6 alloy and mild steel tubes in sacrificial cladding is analyzed in present study. Simplified Concrete Damage Plasticity (SCDP) model is used to define the material behavior of concrete panel of thickness 250 mm. Johnson-Cook (J-C) plasticity model is used to model the stress-strain response of Al 6061-T6 and mild steel tubes, reinforcement bars and steel sheet. ConWep program is used to apply blast pressure on concrete panel [7]. Parametric studies are done for different lengths and metal of tubes in sacrificial cladding. The thickness of tubes is considered 2.9 mm for both the cases. Table 3 shows the peak central displacement of concrete panel with or without sacrificial cladding for different cases.

From FE simulations, it is observed that sacrificial cladding with mild steel tubes performs better in protection of concrete panel from air explosion than sacrificial cladding with Al 6061-T6 alloy tubes. This kind of performance can be attributed to the deformation behavior of tubes during blast loading as shown in Fig. 3 and Fig. 4. During blast in FE simulations, hollow tubes of SC1 collapses progressively and dissipate blast energy by undergoing plastic deformation. It can be seen in Fig. 3 that mild steel tubes deform without buckling and work well in absorbing blast energy. Even after increasing the length of tubes in SC1 by 2 inches from 12.5 cm to 17.5 cm, the tubes undergo progressive failure than buckling. Hence, concrete panel with sacrificial cladding consists of mild steel tubes undergoes less deformation as compared to concrete panel without sacrificial system. Progressive failure is observed in central tube of sacrificial cladding with steel tubes (SC1) as illustrated in Fig. 3.

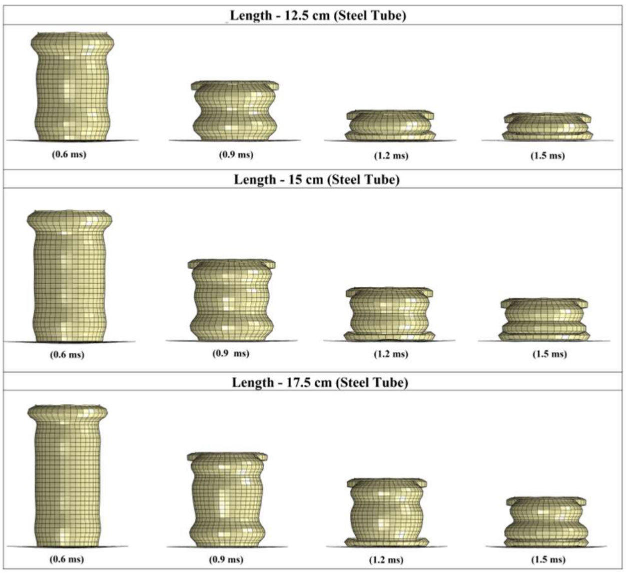

Fig. 3. Deformation behavior of steel tube located at the centre of slab for three different lengths at 0.6 ms, 0.9 ms, 1.2 ms and 1.5 ms for mild steel.

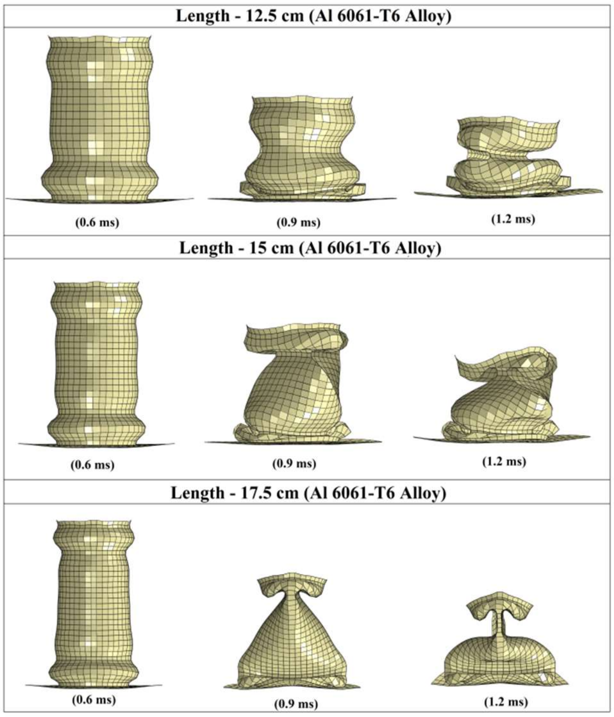

Fig. 4. Deformation behavior of aluminum tube located at the centre of slab for three different lengths at 0.6 ms, 0.9 ms and 1.2 ms for aluminum alloy.

Hollow tubes of SC2 buckled during blast loading. This buckling of tubes restricts the sacrificial cladding to absorb large amount of blast energy. It was also observed that by decreasing the length of tubes up to 12.5 cm from 17.5 cm, the failure behavior of tubes didn't change. Hence, without progressive failure of tubes and lesser absorption of blast energy, concrete panel with sacrificial cladding consist of Al a 6061-T6 tube undergoes large deformation and degradation. In sacrificial cladding with Al 6061-T6 alloy tubes (SC2), buckling can be seen in all the cases considered herein (Fig. 4). The function of tubes in sacrificial cladding is to deform plastically under applied load by absorbing energy. Energy absorption in progressive failure is more than energy absorption in buckling failure due to more plastic deformation in former case. Thus, reduction in peak central displacement in case of sacrificial cladding with mild steel tubes can be seen in Fig. 5. Moreover, for improved understanding, deformation and stress time histories of surface steel plate (provided on tubes and exposed to blast pressure) of sacrificial layer along with stress contours of steel sheet with typical aluminum and mild steel hollow tubes are also shown in Fig. 6 to Fig. 9, respectively. Similar behavior is observed for different variation of sacrificial layer considered in this investigation with different values of stresses and deformation.

In this study, the concrete slab is fixed support on end faces in global X-direction. There is no support on the bottom of concrete slab and failure is predicted to be happening along the Z plane. It is noted that peak displacement at centre point in lower surface of slab is greater than the peak displacement at centre point in upper surface of slab. This behavior is attributed to severe blast wave propagation in concrete [1, 12]. The blast loading acts on steel sheet, which compresses hollow mild steel tubes

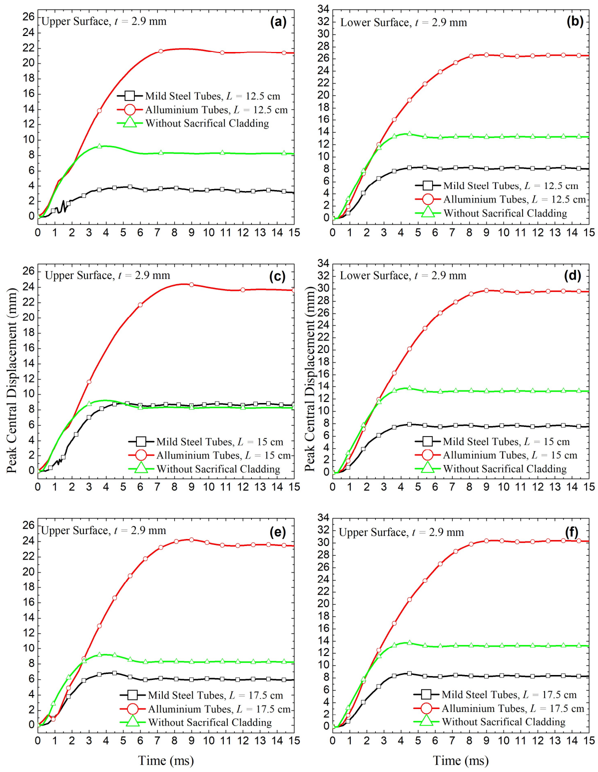

Fig. 5. Displacement histories of centre point on lower and upper surface of concrete panel with or without sacrificial system.

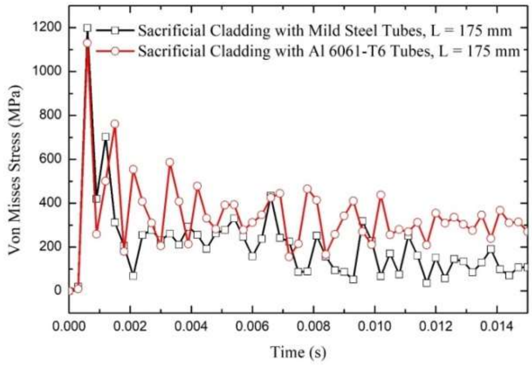

Fig. 6: Stress-time history of central element in steel sheet with sacrificial cladding comprising of 175 mm long mild steel and Al 6061-T6 tubes with outer diameter 60.3 mm.

Table - 3. Peak central displacement of concrete panel

Nomenclature	Length of Tubes (cm)	Peak Central Displacement on Upper/Lower Surface Without Sacrificial Cladding (mm)	Peak Central Displacement of Upper /Lower Surface with Sacrificial Cladding (mm)
SC1	12.5	9.21/13.74	3.87/8.35
	15		8.8/8.35
	17.5		6.83/8.68
SC2	12.5	9.21/13.74	21.96/26.64
	15		23.60/29.54
	17.5		24.22/30.40

completely or partially by absorbing blast energy. After their deformation hollow metal tubes transfer the load directly to concrete slab. In a way, the blast loading on concrete slab act as impact loading through the contact of hollow mild steel tubes and concrete slab (Fig. 1). During both loadings, on the slab's upper surface, concrete slab experiences compression stresses due to propagation of compressive stress wave and may fail if these stresses are greater than compressive strength of concrete. Further, when this compressive stress wave interacts with lower surface of concrete slab, it reflects and converted to tensile stress wave. If this trapped impulse is large enough to overcome concrete's resistance forces, then spalling occurs. In a nutshell, compression occurs at upper surface of slab where as tension occurs at lower surface of slab. As concrete is strong in compression and weak in tension; hence maximum displacement is observed at lower surface. Moreover, in the literature, maximum displacement is always measured on bottom side of the concrete [1-4, 8-13]. Razaqpur et al. [13] used strain gauges on both side of concrete panel in their experimental study. In their result, it was observed that maximum strain on the lower surface of slab is greater than upper surface, in case of normal concrete slab. This is the similar behavior observed in this investigation also.

In addition to above, additional study is carried out to understand the strength degradation of concrete under blast load. Herein, stiffness degradation of concrete is defined by concrete tensile damage (DAMAGET) parameter in SCDP. The value of 0 means the concrete is undamaged whereas value equals to 1 means the concrete is fully damage. Fig. 10 and Fig. 11 shows the cracking pattern on upper and lower surface of concrete panel with or without sacrificial cladding consist of 12.5 cm long mild steel tubes under blast loading. It can be observed in Fig. 10 and Fig. 11 that concrete panel is totally damaged in case of SC2 and partially damaged in case of SC1. Hence, it can be concluded that sacrificial cladding consists of mild steel hollow tubes safeguard the concrete panel better than the sacrificial cladding consist of Al 6061-T6 hollow tubes.

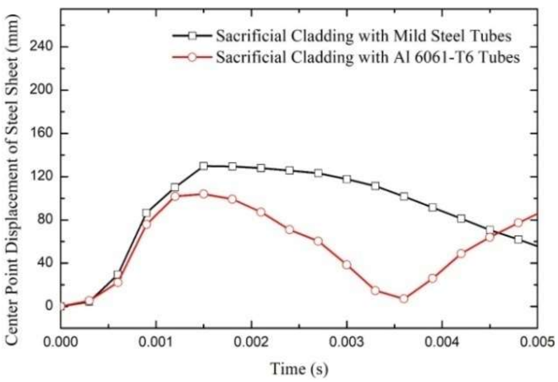

Fig. 7: Displacement-time history at the centre of steel sheet with sacrificial cladding comprising of 175 mm long mild steel and Al 6061-T6 tubes with outer diameter 60.3 mm.

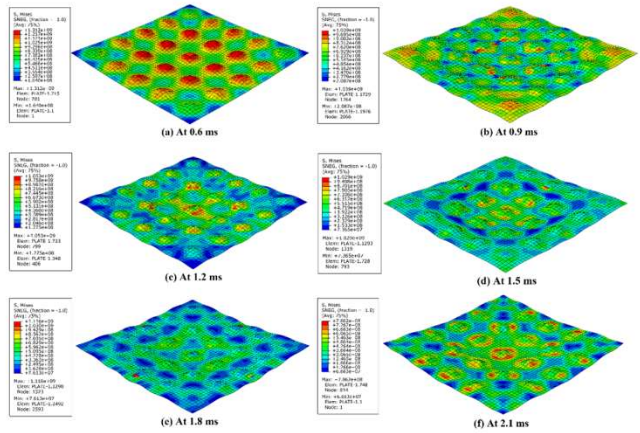

Fig. 8: Stress contours of steel sheet for sacrificial cladding made up of aluminum 6061-T6 hollow tubes with 175 mm length and 60.3 mm outer diameter at varying time (a) 0.6 ms, (b) 0.9 ms, (c) 1.2 ms, (d) 1.5 ms, (e) 1.8 ms, (f) 2.1 ms.

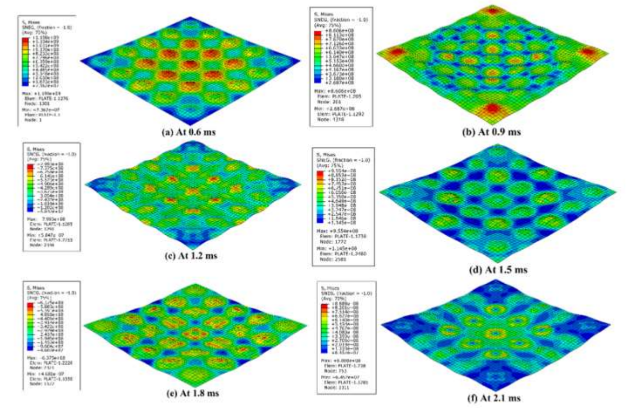

Fig. 9: Stress contours of steel sheet for sacrificial cladding made up of mild steel hollow tubes with 175 mm length and 60.3 mm outer diameter at varying time (a) 0.6 ms, (b) 0.9 ms, (c) 1.2 ms, (d) 1.5 ms, (e) 1.8 ms, (f) 2.1 ms.

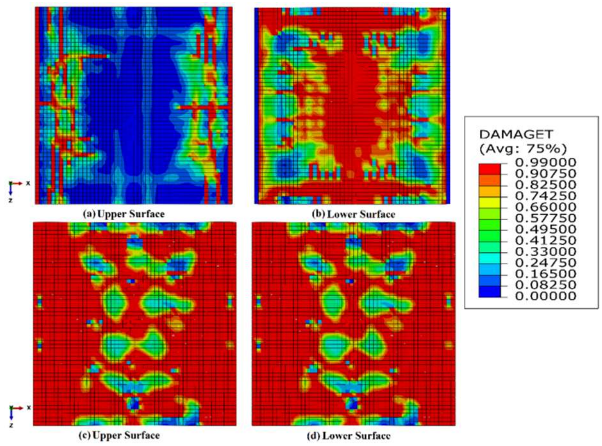

Fig. 10. Cracking pattern of concrete panel under blast loading (a) and (b) on upper and lower surface without sacrificial cladding (c) and (d) on upper and lower surface with sacrificial cladding consist of 60.3 outer diameter mild steel tubes of length 12.5 cm.

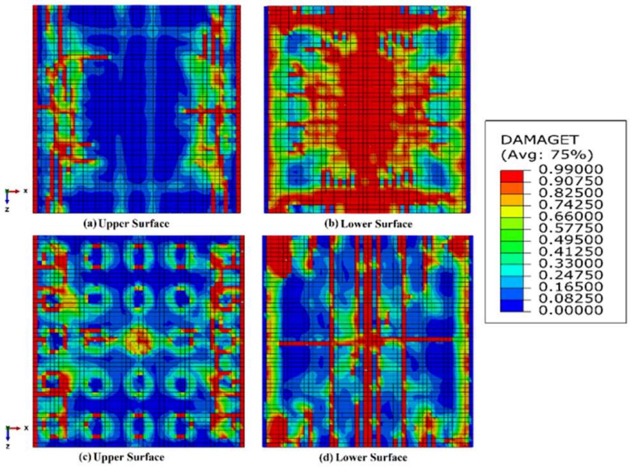

Fig. 11. Cracking pattern of concrete panel under blast loading (a) and on upper and lower surface without sacrificial cladding (c) and (d) on upper and lower surface with sacrificial cladding consist of 60.3 outer diameter mild steel tubes of length 12.5 cm.

5. Conclusions

Herein, a sacrificial cladding is used to protect square concrete panel is analyzed with finite element software ABAQUS/Explicit® [5]. ConWep program developed by US Army is used to apply blast loading with scaled distance of 0.425 m/kg$^{1/3}$ [7]. Sacrificial cladding considered in present study is consisting of hollow metal tubes and steel sheet. Two different metals are used to model tubes in sacrificial cladding, namely Aluminum 6061-T6 alloy and mild steel. The dimension of tubes is considered as per IS1161:1998 [6]. The thickness of steel sheet is considered as 3 mm. Three different lengths of tubes are analyzed for each sacrificial cladding and following conclusions can be drawn based on above investigation.

1. Mild steel tubes undergo progressive failure by absorbing blast energy whereas aluminum 6061-T6 alloy undergo buckling failure.
2. Sacrificial cladding with mild steel tubes performs better in reducing the central displacement of concrete panel than sacrificial cladding with aluminum 6061-T6 alloy tubes.

Disclosures

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