Numerical Studies on Blast Loaded Steel-Concrete Composite Panels

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Abstract*- In this study, response of Steel-Concrete Composite (SCC) panels subjected to air-blast loading is numerically simulated by conducting finite element analysis. A simplified approach to generate the finite element model of the SCC panels is proposed. In the proposed approach, solid, plate and link elements are used to represent the concrete core, steel cover plates and through-through connectors respectively. Interface between the solid and plate elements are idealized with surface-to-surface contact elements, which take care of the transfer of forces between solid and plate elements. Application of the proposed approach for analyzing the SCC components is validated through two examples. Static response of a SCC beam is obtained by using the proposed approach, which is in close agreement with the experimental results. Dynamic response of a SCC panel with through-through connectors subjected to blast pressure due to an explosion of 200 kg TNT at 5 m is obtained by using the proposed simplified approach. Peak response is verified with the results obtained by using an analytical approach. Parametric studies are carried out by varying the charge weight, thickness of the cover plates and diameter of shear connector of the SCC panel. Thickness of the cover plates is found to affect the peak response in a nonlinear manner, while diameter of shear connector is found to have only marginal influence on the peak response.

Keywords- Steel-Concrete Composite; Blast Loading; Peak Displacement; Overpressure; Time-History

I. INTRODUCTION

Structures may experience accidental loads due to blast or impact in addition to other service loads. Blast loads are transient in nature. Peak pressures due to a blast are much greater than that of static collapse load of the structures [1-3]. Structures have to undergo large deformations in order to resist such load, because elastic design is uneconomical and seldom possible. While undergoing such excessive deformation, they should not lose their integrity as well. Concrete is common construction material that possesses large mass, which is essential in blast resistant construction. However, one of the disadvantages of concrete is possibility of spalling and scabbing. An alternate and cost-effective way is to use structural forms that can improve blast resistance. Some of these forms are layered sacrificial cladding, corrugated metal sandwich cores, fibre-metal laminates and steel-concrete composite construction [4-15].

Among the alternatives, steel-concrete composite (SCC) exhibits promising properties for improved blast resistance [4]. This form of construction combines the characteristics of both the materials, namely, steel and concrete in an efficient manner. It is reported in literature, through experimental and analytical studies on SCC panels, that under static as well as close in detonation, SCC structural components perform relatively better than other structural forms [5-13].

Light weight foam core sandwich panels have been analysed by Andrews and Moussa [13] to evaluate their structural response under air-blast loading. Bi-steel panels comprising of two steel plates that are connected together by an array of friction welded transverse bars have been used in blast-resistant construction [14]. The requirement of minimum core thickness in these types of connectors has led to development of slim light weight Steel-Concrete-Steel (SCS) system with J-hook connectors by Liew and Sohel [15].

Theobald et al. [16] performed a numerical parametric investigation on new type of sandwich panels consisting of tubular structure in protective cladding for blast loading. Influence of tube layout within the panel, tube geometry and top plate geometry on the energy absorption properties of the panel has been determined from the investigation.

Numerical investigations on steel-concrete composite structural members are carried out by using the finite element method (FEM). Conventionally, components of the SCC members, namely, concrete core, steel plates / girders and shear connectors are represented by using solid elements [17-20]. In the present study, a simplified finite element modelling approach is proposed for numerical simulation of blast response of SCC panels. The simplified model uses solid, plate and link elements to represent concrete, steel cover plates and shear connectors respectively. Response of a monotonically loaded SCC beam predicted by using the simplified model is found to be in good agreement with that of experimental results, which validates the applicability of simplified model for predicting static response. A SCC panel subjected to air-blast loading is analysed by using the proposed approach. An analytical approach based on equilibrium of forces is used to obtain the peak displacement. This is compared with that of finite element results and is found to be in close agreement, thus validating the proposed approach for dynamic response. This approach is adopted for parametric investigations carried out an SCC panels. Influence of the parameters is studied by comparing the peak response of the panel.

II. FINITE ELEMENT MODELLING APPROACH

FEM is widely used numerical technique for blast analysis [21-24]. Conventional approach of modelling SCC panel is to employ solid elements to discretize all the components, namely steel, concrete and shear connector

[17-20]. This modelling approach results in large number of degrees of freedom (DOF) due to the complex nature of geometry. This poses more demand on modelling requirements.

A. Simplified Approach

A simplified approach is proposed for modelling SCC panels. Based on the characteristics of the components, appropriate elements are identified to represent them. Concrete core, cover plates and shear connectors are idealized using solid, plate and link elements, respectively. Solid elements are eight-noded hexahedral (3D) elements with 3 translational DOF per node. Plate elements are four-noded quadrilateral (2D) elements with 6 DOF per node. Link element is uniaxial (1D) element with 3 DOF per node. This reduces the number of DOF. Interface between concrete and steel plates is modelled using contact pair. Contact and target surfaces constitute a “Contact Pair”. Contact element is located on the surface of plate elements called underlying element. It has the same geometric characteristics as the underlying elements. Target surface is concrete surface facing the plate as shown in Fig. 1. In this study, augmented Lagrangian method of contact algorithm is adopted. The augmented Lagrangian method is an iterative series of penalty updates to find the Lanrange multipliers, i.e., contact tractions. Contact detection points are the integration point and are located at Gauss points. Friction model adopted in this study is Coulomb’s friction model. In this model, two contacting surfaces can carry shear stresses upto a certain magnitude, τ_{lim} across their interfaces before they start sliding relative to each other. Coulomb friction model is defined as:

$$\tau_{lim} = \mu P \qquad (1)$$

$$|\tau| \le \tau_{lim}$$

where,

τ_{lim}= limit shear stress,

τ= equivalent shear stress,

μ= coefficient of friction,

P= contact normal pressure.

This contact pair takes care of the compatibility between solid and shell elements at their interfaces.

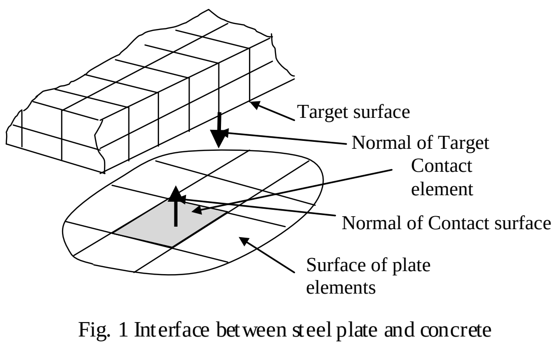


Fig. 1 Interface between steel plate and concrete

III. NUMERICAL VALIDATION

Validation of the proposed simplified approach is carried out by analysing two SCC structural components. In the first example, a SCC beam is subjected to monotonic loading. Load-deflection response of the beam obtained from the FE analysis and experiments are compared. In order to ascertain that the proposed approach can be used for dynamic response as well, a SCC panel subjected to air-blast loading is analysed. Numerical results are verified with that of an analytical model.

A. Static Response

The proposed simplified approach is validated by analysing a SCC beam with through-through connectors subjected to static load. Overall length of the beam is 2.2 m, while width and depth of the beam are 400 mm and 200 mm, respectively. The compression and tension plate thicknesses are 11.93 mm and 6.2 mm, respectively. Connectors of 25 mm diameter are equally spaced at 300 mm c/c between the simply supported span of 1.8 m. The beam contains two rows of connectors spaced at 200 mm c/c. Characteristic compressive strength of concrete used is 40 MPa. Properties of steel used for plate and connector are summarized in Table I. Multi-linear material model is used to represent the behaviour of concrete, while steel behaviour is represented by using bilinear stress-strain curve. Beam is subjected to central concentrated load. Details of the beam are shown in Fig. 2.

TABLE I PROPERTIES OF STEEL

Component	Yield Strength, MPa	Ultimate Strength, MPa
Plate	384	507
Connector	541	566

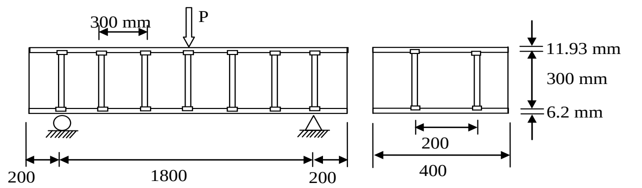


Fig. 2 Details of Steel-Concrete Composite Beam

Two approaches are used to model the beam. In the first approach, solid elements are used to represent the entire composite beam, while in the second approach, proposed simplified model is used. Surface to surface contact is applied on interfaces between steel and concrete. Nonlinear static analysis is carried out to obtain the load-deflection response. Responses from both approaches are compared with that of the experimental results available in literature [25] as shown in Fig. 3.

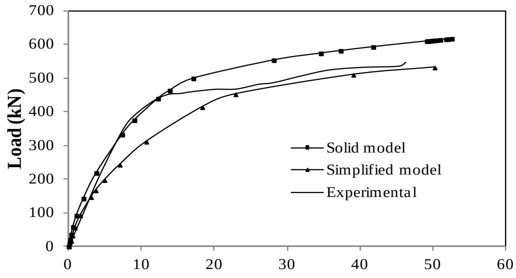


Fig. 3 Load-deflection response of SCC beam

Results of the solid model are found to be in close agreement with that of experiments up to yield load. Stiffness of the load-deflection curve obtained by using the simplified approach is found to be less than that of experiment. Yield load, ultimate load, yield and ultimate deflections predicted by the solid model and simplified models compared with experimental values are shown in Table II. Difference between prediction of ultimate load and deflection and experimental value is less than 10%, while yield load and deflection are predicted with about 16% difference. From the results given in Table II, simplified approach is found to be computationally efficient, without losing the accuracy in prediction of the responses of steel-concrete composite panel.

TABLE II COMPARISON OF RESPONSE OF BEAM WITH THROUGH-THROUGH CONNECTORS

	Experiment	Solid Model	Simplified Model
Yield load, kN	333	360	280
Ultimate load, kN	545	616	530
Yield deflection, mm	7.1	8.44	9.02
Ultimate deflection, mm	46.25	52.59	50.24

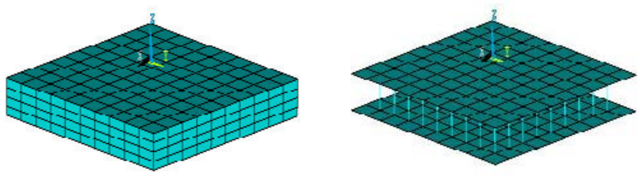
B. Dynamic Response

To ensure the applicability of the simplified approach for blast response analysis, a SCC panel subjected to air blast loading is solved by conducting finite element analysis. Results from the analysis are compared with that obtained using an analytical model proposed by Coyle and Cormie [26].

Dimensions of steel-concrete composite panel are 2m x 2m. The panel is simply supported on all four sides. Through-through connectors of diameter 16 mm are provided at a spacing of 200 mm c/c in both directions. Concrete core thickness is 200 mm and thickness of the plates on either side is 6 mm.

Simplified approach described earlier is used to model the panel. Load transfer from concrete to steel plates is realised through the shear connector and interface between steel and concrete surfaces is modeled using surface to surface contact. Fig. 4 shows the finite element model of the panel.

Properties of the concrete and steel used in the study are given in Table III. Steel behaviour is idealized using bilinear stress-strain model (Fig. 5a) and a parabolic curve is used to characterise the behaviour of concrete (Fig. 5b).

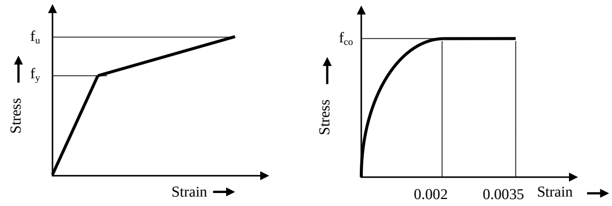


(a) Panel with concrete core (b) Steel plates and shear connector

Fig. 4 Finite element model of the panel

TABLE III PROPERTIES OF CONCRETE AND STEEL

Parameter	Material	
	Steel	Concrete
Yield stress (MPa)	350	-
Young's modulus (GPa)	200	31.62
Cube strength (MPa)	-	40



(a) Steel (b) Concrete

Fig. 5 Material model used in the study

Blast pressure due to explosion of 200 kg TNT at 5 m distance from the panel is computed and is shown in Fig. 6. Nonlinear transient dynamic analysis is carried out with time step of 0.00001 sec. Responses in terms of transverse displacement at centre of panel are obtained. Fig. 7 shows the displacement time history at centre point of the panel. Peak displacement is found to be about 17.6 mm as observed from Fig. 7.

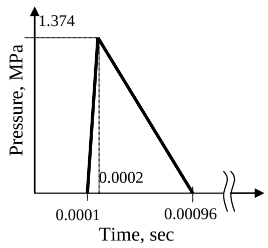


Fig. 6 Pressure time history

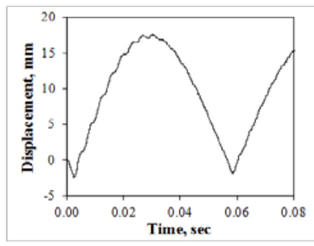
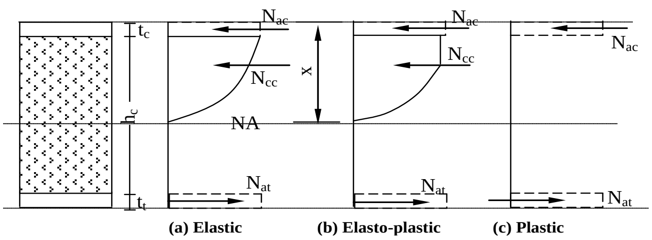


Fig. 7 Time history of displacement at centre of the panel

C. Analytical Model

Cross-section of steel-concrete composite panel and the stress variation along its depth are illustrated in Fig. 8. When the panel is in elastic state, bottom plate experience tension and top plate and concrete above neutral axes are in compression (Fig. 8(a)). On further loading the panel, stress variation across the cross-section in the elasto-plastic state is as shown in Fig. 8(b). In both the cases, concrete above neutral axis contributes to the moment capacity of the section. At ultimate stage, capacity of the section is only due to the outer steel plates and is as shown in Fig. 8(c).



N_{cc} – force in concrete in compression
N_{ac} – force in steel plate in compression
N_{at} – force in steel plate in tension

Fig. 8 Cross-section of steel-concrete composite panel

Depth to neutral axes is calculated by applying equilibrium of forces. Second moment of area I_b is calculated based on the transformed section. A factor ‘c’ is applied to I_b to obtain the effective moment of inertia, I_{eff}. Effective stiffness, k_e which is function of I, E and L is obtained from standard charts available in TM5-1300 [27]. Peak deflection of the panel is calculated based on the procedure described in Coyle and Cormie [26] and is as given below:

Maximum resistance of the section, R_m is calculated for simply supported condition and subjected to uniformly distributed load using the following equation:

$$R_m = \frac{12}{a}\left(M_{Pa} + M_{Pb}\right) \quad (2)$$

where,

$M_{Pa=}$ total positive ultimate moment capacity along midspan section parallel to short edge / m,

$M_{Pb=}$ total positive ultimate moment capacity along midspan section parallel to long edge / m,

a= short span,

b=long span.

$M_{Pa} = M_{Pb} = M_R$, which is given by:

$$M_R = tf_y\left(h_c + t\right) \quad (3)$$

where,

$M_{R=}$ moment of resistance,

$t= t_c = t_t$,

t= thickness of compression steel plate,

t= thickness of tension steel plate,

h= thickness of concrete core,

$f_{y=}$ yield stress of the steel plate

Depth to neutral axis, ‘x’ is given by:

$$x = -B + \sqrt{B^2 - 2C} \quad (4)$$

where,

$$B = a_e t_c + a_e t_t - t_t \quad (5)$$

$$C = -Da_e t_c + \frac{t_t^{\,2} a_e}{2} + \frac{t_c^{\,2} a_e}{2} + \frac{t_c^{\,2}}{2} \quad (6)$$

D= overall thickness,

$$a_e = \frac{E_s}{E_c} \quad (7)$$

Second moment of area of unit width of the panel, I_b is calculated as:

$$I_b = bt_c\left(x - \frac{t_c}{2}\right)^2 + \frac{b}{a_e}\frac{(x-t_c)^3}{3} + bt_t\left(D - x - \frac{t_t}{2}\right)^2 \quad (8)$$

Due to reduced shear stiffness that results from slip between the face plates and concrete, effective second moment of area, I_{eff} is obtained by multiplying second moment of area with a factor c, which is calculated from:

$$c = \frac{\delta_b}{\delta_b + \delta_s} \quad (9)$$

where δ_b and δ_s are deflections due to unit bending and shear loads respectively.

Effective shear stiffness, G’, which is required in calculation of δ_s is determined from empirical equation.

$$G' = 4.53 \times 10^5 \left(\frac{t_t + t_c}{s_x^{\,0.7} s_y}\right) - 310 \quad (10)$$

where s_x and s_y are the shear connector spacing in the primary and secondary span directions respectively and t_c, t_t, s_x and s_y are in mm and the calculated G’ is in N/mm^2.

Effective stiffness of unit width of the panel, k_e is obtained from

$$k_e = \frac{252EI_{eff}}{a^2} N/m \quad (11)$$

Elastic deflection of the panel, X_e is obtained from

$$X_e = \frac{R_m}{k_e} \quad (12)$$

Basic impulse equation is obtained by equating areas under resistance deflection curve (Fig. 9) and pressure time curve (Fig. 10) and is

$$\frac{i_2 A_2}{2K_{LM}M} = \frac{R_m X_e}{2} + R_m\left(X_m - X_e\right) \quad (13)$$

where,

$K_{LM=}$ load-mass factor given in IS: 4991-1968,

$X_{m=}$ maximum deflection attainable by the section,

i= unit impulse,

A= area on which blast pressure ‘p’ is acting,

M= mass of panel.

In Equation (13), all other values except X_m are known. Therefore,

$$X_m = \frac{\left(\frac{i_2 A_2}{2K_{LM}M}\right) + \frac{R_m X_e}{2}}{R_m} \quad (14)$$

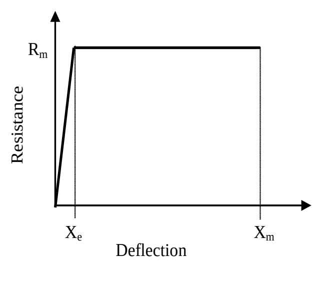


Fig. 9 Idealized resistance-deflection curve [26]

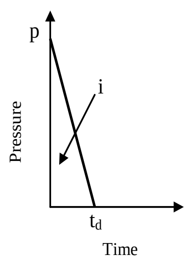


Fig. 10 Idealization of blast load [26]

The value of peak displacement corresponding to the blast loading chosen in the example is calculated to be 16.7 mm using the above procedure. This value is in close agreement with the peak displacement of 17.6 mm obtained from the finite element analysis. Thus, the simplified approach can be used for modeling the steel-concrete composite panels subjected to blast loading.

IV. NUMERICAL STUDIES

A steel-concrete composite panel of 2 m x 2 m size with through-through connectors spaced at 200 mm c/c in both the directions is taken up for study. Size of the connector is kept as 16 mm. Concrete core thickness is 200 mm, while steel cover plates are of 6 mm thickness. This panel is subjected to air-blast loading due to a charge at 5 m distance from the centre of the panel as shown in Fig. 11.

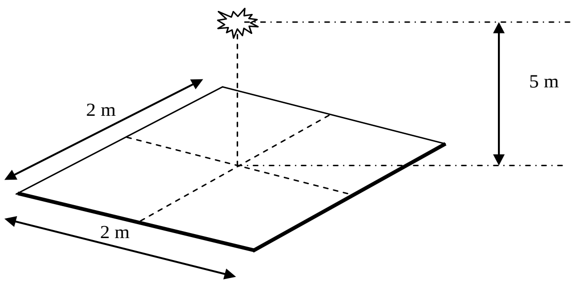


Fig. 11 Charge weight location

A. *Charge Variation*

Charge at 5m distance is varied from 100 kg TNT to 400 kg TNT. Pressure time histories due to explosion of these charges are generated. Panel is modeled using the simplified approach. Nonlinear transient dynamic analysis is carried out. Fig. 12 shows the time history of the displacement at centre of the panel for different charge weights. From Fig. 12, it can be observed that the peak displacement increases with the charge weight. Analyses are repeated for different plate thicknesses of 8 mm, 10 mm and 12 mm. Variation of peak central displacement with charge weight is plotted in Fig. 13. Peak displacement is found to vary in a nonlinear manner with charge and is proportional to the impulse as observed from Fig. 13. It can also be noted that similar trend of variation is observed for all plate thicknesses. Fig. 14 shows variation of time period of response with charge weight. This variation is found to be in similar trend as observed in Fig. 13.

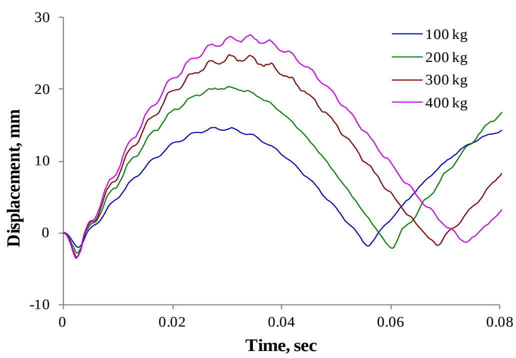


Fig. 12 Time history of displacement

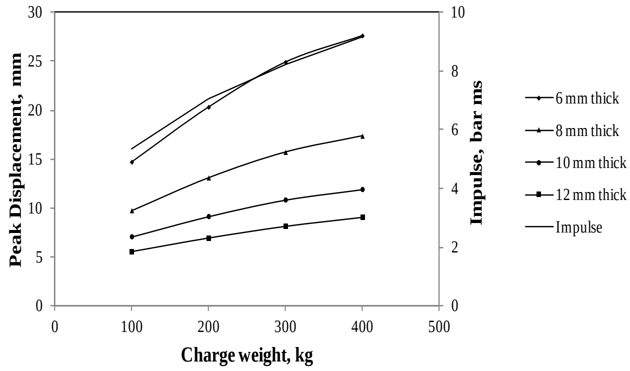


Fig. 13 Variation of peak displacement with charge weight

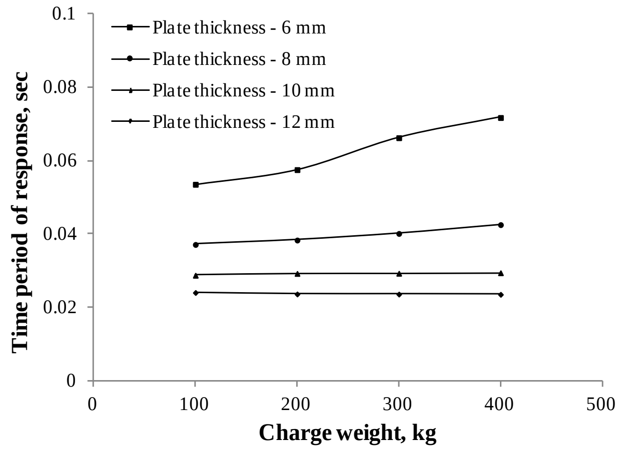


Fig. 14 Variation of time period of response with Charge weight

B. *Thickness Variation*

Thickness of the cover plates is varied from 6 mm to 12 mm with increments of 2 mm. All other parameters are kept same as above. Panel is subjected to pressure loading due to explosion of 100 kg TNT at a distance of 5m. Time history of displacement is shown in Fig. 15. Peak displacement at centre of the panel is obtained. This set of analysis is repeated for 200 kg, 300 kg and 400 kg TNT. Variation of peak displacement with thickness is plotted in Fig. 16. It can be observed that the variation is nonlinear. Similar trend is observed for all charge weights. Time period of response is plotted for all plate thicknesses as shown in Fig. 17. Similarity of variation of peak displacement in Fig. 16 and that of time period of response in Fig. 17 can be observed.

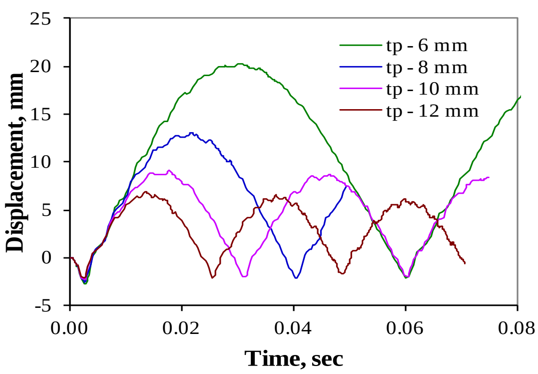


Fig. 15 Time history of displacement for 200 kg TNT

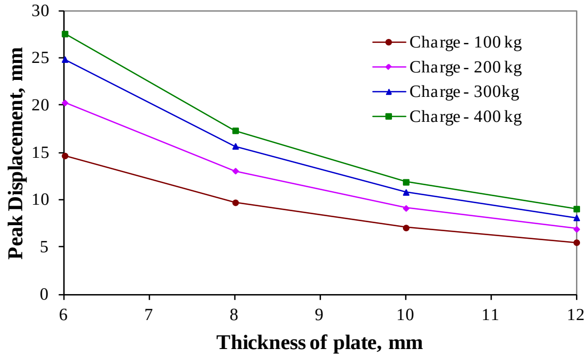


Fig. 16 Variation of Displacement with Thickness

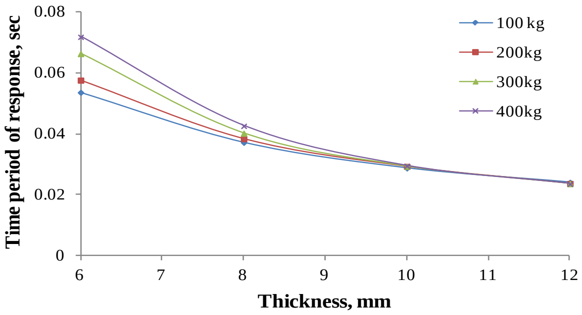


Fig. 17 Variation of time period of response with thickness of plate

C. *Diameter Variation*

The diameter of connector is varied as 16 mm, 20 mm and 25 mm, and all other parameters are kept constant, namely, spacing of connector, charge weight and plate thickness. Spacing of connector is kept as 200 mm while charge weight is 100kg. Thickness of plate is 6mm. Diameter of connector is found to have only negligible influence on the peak response as observed in Fig. 18.

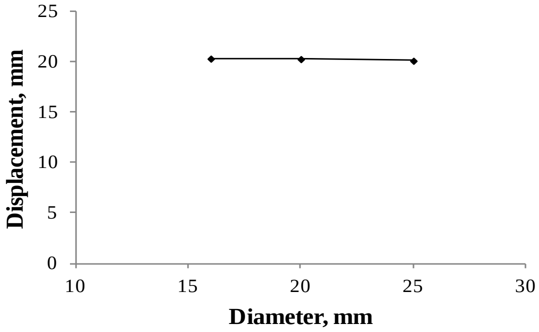


Fig. 18 Variation of peak displacement with connector diameter

V. CONCLUSIONS

Conventional approach for finite element modeling of steel-concrete composite (SCC) panels is to employ solid elements to represent all the components of the SCC panels. In this paper, a simplified approach of modeling the steel-concrete composite panel subjected to air-blast loading is proposed to simulate the behavior. This approach is computationally efficient and requires less modeling effort. A SCC beam subjected to static load at centre is analyzed using the proposed approach. Ultimate load and deflection are predicted with less than about 10% difference with that of experimental values, while yield load and deflection are predicted with about 16% difference. Dynamic response of the SCC panel modeled using proposed approach is verified using an analytical model. Peak displacement predicted by using the proposed approach is 17.6 mm, while that by using the analytical study is 16.7 mm. The use of the proposed approach to analyze SCC panel is thus justified. Parametric studies are conducted to find out their influence on peak response. Plate thickness is found to influence the response in a nonlinear manner, while diameter of connector has only negligible influence. Variation of displacement with charge is found to be nonlinear and is proportional to the impulse.

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