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Performance Assessment of Curved Steel Wall under Blast Loading

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***Abstract:*— Structural engineering strategies can improve the blast resisting capacity of the elements. Blast resistance performance of elements can also be improved by varying geometry of the elements. In the present investigation, dynamic analysis of steel sacrificial blast wall is carried out with varying angle of curvature and thickness of wall. Three-dimensional nonlinear dynamic analysis of steel wall under blast loading has been carried out using ABAQUS® finite element package. Trapezoidal impulse with uniform pressure has been considered for defining blast loading. Performance of wall is compared with equivalent triangular loading to understand the effect on peak deflection. Three-dimensional deformable shell element (S4R i.e. 4-noded doubly curved thin or thick shell, reduced integration, hourglass control and finite membrane strains) has been used for FE analysis of wall. Analysis has been carried out with varying angle of curvature along top one-fourth length of wall. Performance of curved walls is compared with that of straight vertical wall in terms of peak deflection. Further, effect of thickness of wall, on the blast resistance, has been investigated. Deflection at various points along the height of wall and strain energy curves of wall are also computed and analyzed. From the present analysis, it is observed that variation in angle of curvature of wall results in considerable improvement in performance of wall against blast loading. Models with trapezoidal blast loading and equivalent triangular loading shows almost similar results. Increase in thickness of wall results in reduced deflection against blast loading.**

***Index Terms* :-- Blast, Curved Steel Wall, ABAQUS®/Explicit, Dynamic Response.**

I. INTRODUCTION

Blasts due to intentional or accidental causes are on their raising frequencies in recent years [1]. It has been noticed that blasts becoming more vulnerable due to secondary effects which involves fragments hitting the people or buildings near the explosion, structural collapse, and debris impact. Secondary effects are formed by structural failure of elements which are exposed to the blast loading directly. Damage due to blast can be minimized by strengthening the elements of structure which can be exposed to the blast loading, so as to avoid the secondary damage factors. Providing sacrificial blast wall will reduce the effect of blast load reaching the important structures which need to be protected. Strengthening of sacrificial blast wall can be achieved by using structural engineering strategies such as by modifying the geometry of wall.

Goel and Matsagar [2] had investigated the mitigation strategies in design of structures to exhibit improved blast resistance as well as with maintaining architecturally appealing appearance. Nguyen *et al.* [3] studied effect of pressure of blast load, its location and effect of damping ratio of shell under blast loading. Linkute *et al*. [4] had carried their research on probabilistic design of sacrificial cladding for a blast wall using limited statistical information on blast loading. Goel *et al*. [5] investigated the dynamics response of stiffened plates with various stiffener layouts sandwiched between two steel plates subjected to air blast. Nickerson *et al.* [6] carried Finite Element (FE) evaluation of blast design response criteria for load-bearing precast wall panels. Matsagar [7] had carried out analysis on computation of stress and displacement response of composite plates under blast loading.

Still there exists further scope for investigation of wall considering their geometry. Hence, in the present investigation, numerical analysis of blast wall has been carried to understand the performance of curved sacrificial wall under blast loading using ABAQUS® finite element (FE) package. The present research is primarily focused on numerical analysis of blast resistant wall with varying angle of curvature of wall along the vertical face. Further, investigation of wall under varying thickness has been carried. Deflections of wall at various points along the length of wall vertically and strain energy of wall are investigated to study the performance of wall. Moreover, performance of blast wall with trapezoidal blast loading has been compared with that of equivalent triangular loading.

II. FINITE ELEMENT MODELLING

Three-dimensional nonlinear dynamic analysis of steel wall under blast loading has been carried out using ABAQUS® finite element package. Three-dimensional deformable shell element (S4R i.e., 4-noded doubly curved thin or thick shell, reduced integration, hourglass control and finite membrane strains) has been used for FE analysis of wall. Wall of size 2 m × 2 m is considered with x-axis parallel to the normal of wall surface. For curved walls, one-fourth portion of wall from top is considered to be curved with respect to the axis parallel to z-axis. Finite element models of straight wall and curved walls have been developed with angle of curvature (θ) varying from 0° to 90° with a regular interval of 15°. Angle of curvature (θ), Radius of curvature (R), horizontal offset (H) and vertical offset (V) considered for modeling the curved portion of wall as shown in Fig. 1 and their corresponding details are reported in Table I.

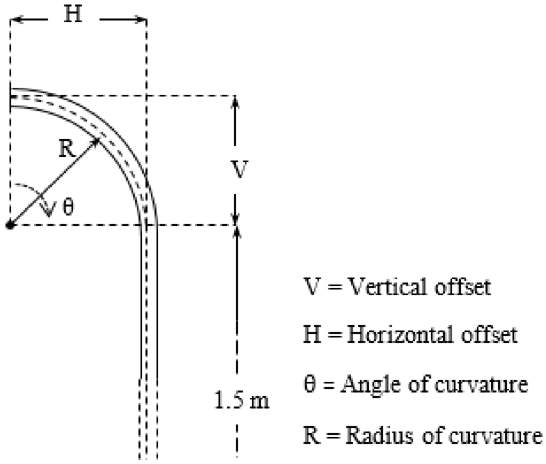

Fig. 1: Geometrical features of curved portion of wall.

Table I: Geometrical design parameters of curved walls with varying angle of curvatures.

Angle of curvature (Degrees)	Horizontal offset (m)	Vertical offset (m)	Radius of curvature (m)
0°	0	0.500	0
15°	0.065	0.494	1.909
30°	0.128	0.477	0.955
45°	0.187	0.450	0.636
60°	0.239	0.413	0.477
75°	0.283	0.369	0.382
90°	0.318	0.318	0.318

III. MATERIAL PROPERTIES, LOADING AND BOUNDARY CONDITIONS

Elastic and plastic material properties of steel are considered as reported by Goel *et al.* [5]. Plastic strain parameters varying with yield stress considered for plastic behavior of steel wall are shown in Table II. Mass density, Young's modulus and Poisson's ratio of steel are considered as 7800 kg/m^3, 210 GPa, 0.03, respectively.

Table II: Stress-strain parameters of steel [5].

Yield stress (Pa)	Plastic strain
300×10^6	0
350×10^6	0.025
375×10^6	0.1
394×10^6	0.2
400×10^6	0.35

Base of wall is considered as fixed with ENCASTRE (U1 = U2 = U3 = U4 = U5 = U6 = 0) boundary condition as available in ABAQUS®. Sides of wall are considered as hinged with displacement type (U2 = U3 = UR1 = 0) boundary conditions. Uniform pressure loading of unit magnitude with varying amplitude is considered. Trapezoidal impulse with uniform pressure has been considered for defining blast loading. Performance of wall is compared with equivalent triangular loading to understand the effect of blast profile on peak deflection. Trapezoidal and equivalent triangular profiles considered in the present investigation are shown in Fig. 2.

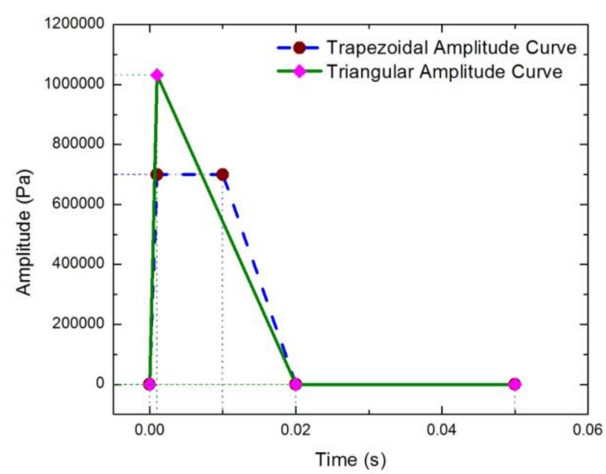

Fig. 2: Blast load profiles considered in the present investigation.

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IV. VALIDATION OF FE SCHEME

Details of Validation:

Jain *et al*. [8] carried their research on dynamic response of reinforced concrete wall subjected to blast loading. In their analysis, displacement values of wall at its center point, with standard grade of concrete of M25, with varying grades of steel reinforcement Fe250, Fe415 and Fe500 are calculated from the similar models prepared in ABAQUS® FE package.

Preparation of FE model for validation:

Wall is modelled using three dimensional, deformable shell of extrusion type. A wall of 2 m × 2 m is developed with y-axis as the normal to the plane of wall. Elastic material properties of concrete and steel are considered. Concrete damaged plasticity is considered for concrete material property. In plasticity data, dilatation angle of 31°, eccentricity of 0.1, f_{b0}/f_{c0} value of 1.16, K value of 0.667 and viscosity parameter value of 0, is considered. Yield stress of 130 MPa with zero inelastic strain has been considered for compressive behavior of concrete damaged plasticity. Yield stress of 3.5 MPa (= 0.7 $f_{ck}^{0.5}$) with zero cracking strain has considered for tensile behavior of concrete damaged plasticity. Yield stress of 415 MPa with zero plastic strain has considered as plastic data. Both stress-strain responses of concrete and steel have been considered as strain rate independent. Pressure magnitude is mentioned as one and predefined tabular amplitude curve is selected for amplitude input. Fixed boundary condition is chosen with ENCASTRE (U1=U2=U3=UR1=UR2=UR3=0) on four sides of wall. Mesh type of S4R (A 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains) with part size of 0.1 is considered.

Comparison of results

The maximum deflection curves of walls with varying grades of steel reinforcement (Fe250, Fe415 and Fe500) are plotted for same grade of concrete of M25, thickness of wall 0.2 m, diameter of reinforcing bar of 0.01 m, percentage of steel of 0.25%. Further, the present FE scheme results are compared with results reported by Jain *et al*. [8] as shown in Fig. 3. It can be observed from this figure that results computed using present FE analysis are well in agreement with those reported Jain *et al*. [8], thus validating the present FE scheme.

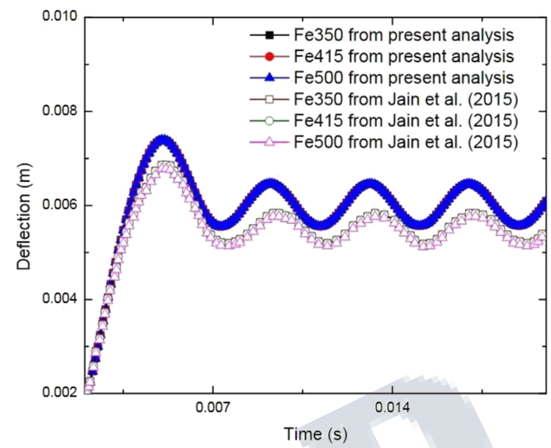

Fig. 3: Comparison of deflection of present FE model results with Jain et al. [8].

V. RESULTS AND DISCUSSIONS

Study with varying blast profile:

Blast resistant walls with thickness (t_w) of 0.03 m is analyzed with varying angle of curvature from 0° to 90° with a regular interval of 15°. A total seven models are analyzed with trapezoidal loading. Further, performance of wall is compared with equivalent triangular loading to understand the effect on peak deflection. To analyze the performance of wall, deflection curves of wall in x-axis at 1.5 m and 2 m from base measured along the vertical face of wall are investigated. Strain energy curves (ALLSE) of wall are also investigated for performance study of blast resistant walls.

Deflection curves of wall with varying angle of curvatures at 1.5 m and 2 m from the base of the wall measured along height of wall are shown in Fig. 4 and Fig. 5 for triangular loading, respectively. Similar behavior is observed in case of trapezoidal loading. Variation in strain energy (ALLSE) of the wall with varying angle of curvature of wall is shown in Fig. 6.

Fig. 7 and Fig. 8 shows the maximum deflections of walls with varying angle of curvatures at 1.5 m and 2 m measured from the base along the wall respectively. Fig. 9 shows the maximum strain energies (ALLSE) with varying angle of curvature of wall.

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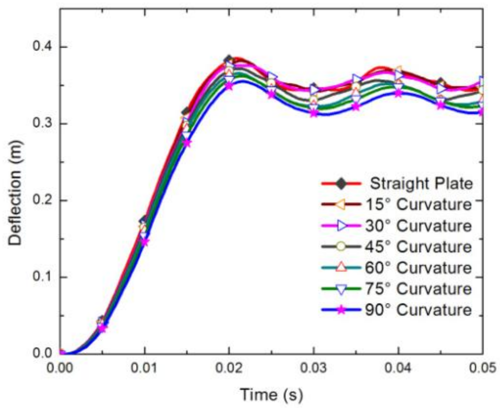

Fig. 4: Displacement time histories of wall at 1.5 m from base with triangular loading.

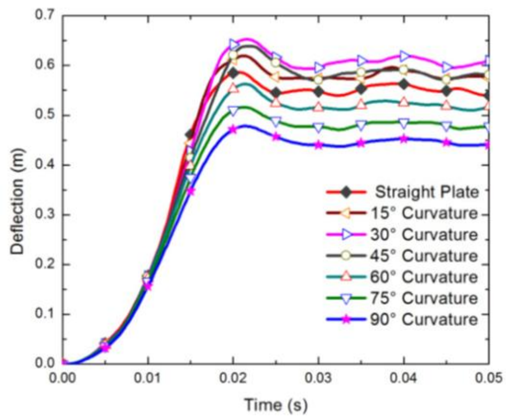

Fig. 5: Displacement time histories of wall at 2 m from base with triangular loading.

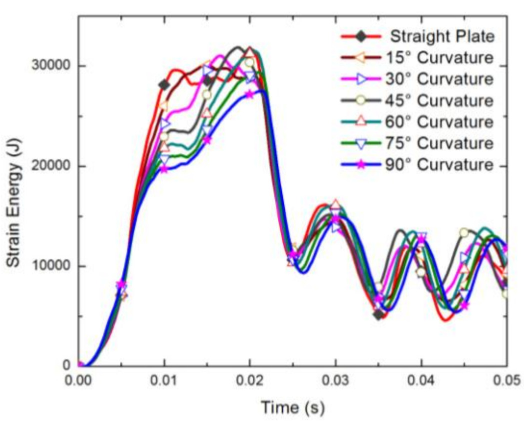

Fig. 6: Strain Energy (ALLSE) curves of wall with triangular loading.

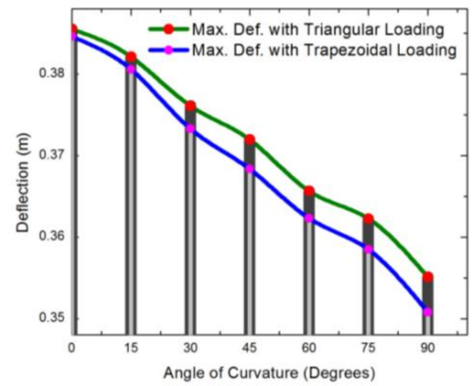

Fig. 7: Maximum deflection of wall at 1.5 m from base with triangular and trapezoidal loading.

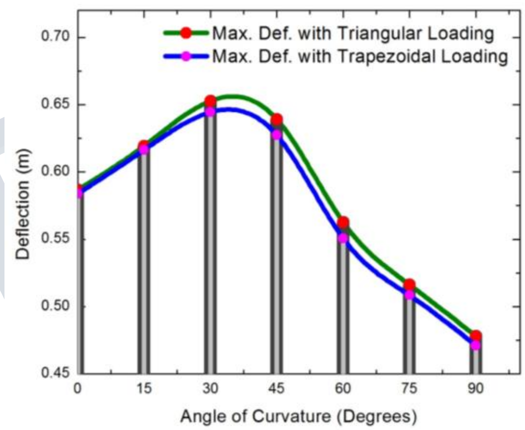

Fig. 8: Maximum deflection of wall at 2 m from base with triangular and trapezoidal loading.

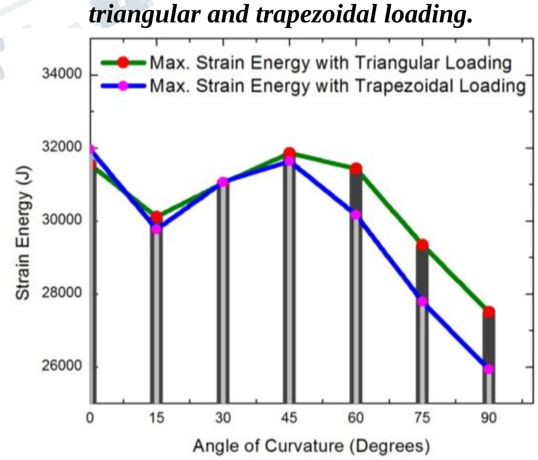

Fig. 9: Maximum strain energy (ALLSE) of wall with triangular and trapezoidal loading.

From the analysis, it is noticed that models with triangular and trapezoidal loadings shows almost similar performance. Table III shows the variation of results of models with trapezoidal loading from that of triangular loading in percentages.

Table III: Variation of results of trapezoidal loading with that of triangular loading.

Curvature Angle (Degrees)	**Variation in deflection at 2 m (%)**	**Variation in deflection at 1.5 m (%)**	**Variation in Strain Energy (%)**
0°	0.502	0.234	-1.287
15°	0.472	0.405	1.147
30°	1.272	0.746	-0.098
45°	1.847	0.969	0.697
60°	2.143	0.916	4.034
75°	1.517	1.040	5.308
90°	1.448	1.217	5.723

Study with varying thickness of wall:

Blast resistant walls with thicknesses (t_w) of 0.02 m, 0.03 m and 0.04 m are analyzed with varying angle of curvature from 0° to 90° with a regular interval of 15°. A total seven models of varying angle of curvatures are analyzed for each thickness of wall considered with equivalent triangular loading. Further, performance of wall is compared to understand the effect on peak deflection. To analyze the performance of wall, deflection curves of wall in x-axis at 1.5 m and 2 m from base measured along the vertical face of wall are investigated. Strain energy curves of wall are also investigated for performance study of blast resisting walls.

Fig. 10 and Fig. 11 shows the maximum deflections with varying thickness of wall at 2 m and 1.5 m measured from the base along the wall, respectively. Fig. 12 shows the maximum strain energies (ALLSE) with varying thickness of wall.

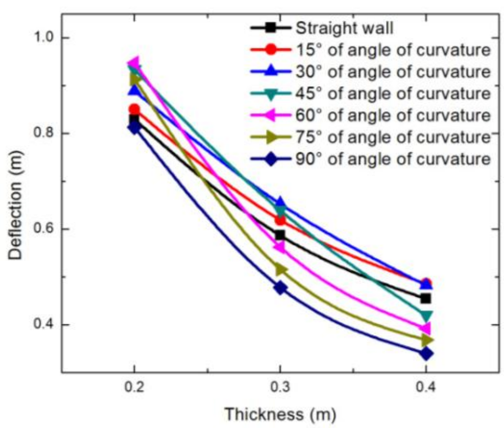

Fig. 10: Maximum deflections with varying thickness of wall at 2 m

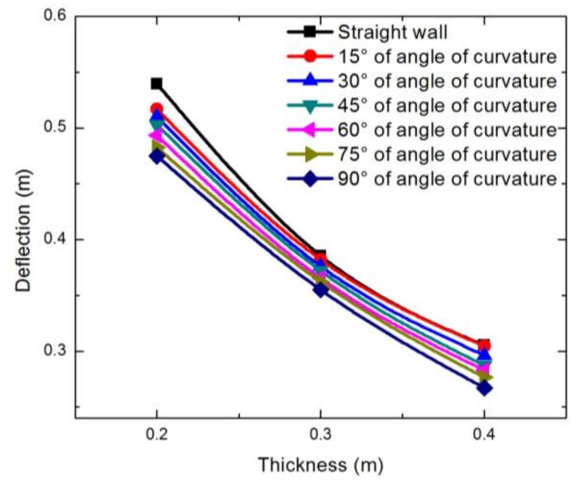

Fig. 11: Maximum deflections with varying thickness of wall at 1.5 m.

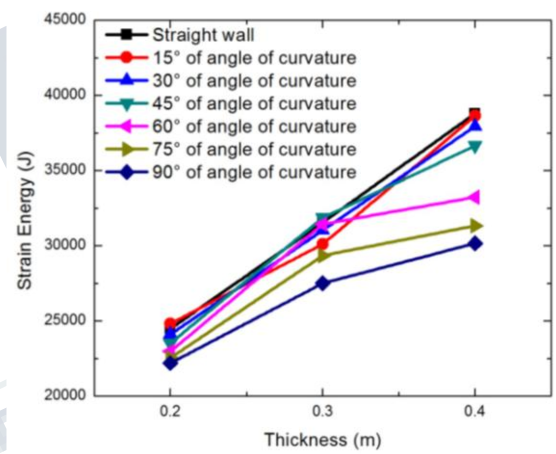

Fig. 12: Maximum strain energies (ALLSE) with varying thickness of wall.

From the results, it is noticed that deflection of wall is decreasing with the increase in thickness of wall whereas, strain energy is increasing with increase in thickness of wall.

VI. CONCLUSIONS

From the present analysis, it is observed that by varying angle of curvature of wall, performance of wall is improved under blast loading. With the increasing thickness of wall the maximum deflection of wall at 2 m from base of wall increased till 45° and further decreased from 60° to 90°. At 1.5 m from base of wall the maximum deflection is decreasing with increase in angle of curvature of wall. Varying the angle of curvature of wall varying the strain energy of wall as well. Performance of wall under blast loading is improved with increase in thickness of wall. Deflection of wall at both 1.5 m and 2 m from base decreased with increasing thickness of wall. Strain energy of wall is increased with the increase in thickness of wall.

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