Impact Analysis of Steel Plated Concrete Wall

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ABSTRACT

Impact analysis of nuclear plant structural walls composed of surface steel plates, tie-bars, shear studs and concrete are discussed utilizing a simplified model of a fictitious wall to perform the analysis using LS-DYNA. The concrete constitutive model is based on Winfrith concrete model which covers all aspects of concrete behavior including cracking. The model was used to conduct a series of numerical studies to evaluate the effect of several parameters affecting the behavior of the wall. These parameters include thickness of the wall, thickness of the steel plate and diameter of tie bars. These studies resulted in several conclusions regarding the global and local behavior of the steel plated concrete wall system.

INTRODUCTION

Steel plated concrete (SC) walls are composite members in which the concrete outer surfaces are reinforced with steel plates, and the steel plates and concrete are combined together with the help of tie bars and headed studs. The SC type construction can significantly reduce the time and increases the quality of the construction (Takeuchi et al 1998, Akita et al 2001).

The SC wall construction is becoming more common in nuclear structures because the inside liner plate can be intact due to external loads, and even with an extensive concrete damage, concrete will not spall into the work area and also the structure will not have radioactive leakage (Sugano et al. 1993, Mizuno et al. 1999).

The behavior of the impact loading on the SC structures is dependent on the structural strength and intensity of the impact. The analytical modeling of the behavior of SC structures under impact loading has received considerable attention in recent years. This is because several experimental studies have been conducted to evaluate the behavior of SC members against the impact loads and the recent increase in the use of SC type construction in nuclear structures.

In this study, impact analysis of the SC wall is conducted utilizing a fictitious wall to perform the analysis representing the loading by the Riera force history method (Riera, 1968, 1980) which represents the aircraft impact loads. The detailed
results and parameters of plane such as weight, speed, materials and thickness are not presented. The LS-DYNA finite element program (LSTC, 2010) with an appropriate material constitutive model is used as an analysis tool.

FINITE ELEMENT MODEL

A three-dimensional (3-D) finite element model of the rectangular SC wall is developed in LS-DYNA and the analysis was performed using LS-DYNA explicit solver. The geometric size of the wall is 190 ft long, 60 ft high with different thicknesses ranging from 3 ft (36 in) to 8 ft (96 in) (Figure 1). To simplify the model, shear studs in the wall are not explicitly modeled. However, node sharing technique is used between the steel plate shell element and the contact surfaces of the concrete elements so that the steel plates are “glued” to the concrete surface with strains compatible with concrete. Because of this the element size of the liner plate is similar to the concrete element. Tie bars are embedded in concrete mass and the end nodes of the tie bars and rebar are tied to the liner plate using the node to surface tie option in LS-DYNA (Figure 2(a)).

An eight-node solid element with reduced integration scheme is used to model the concrete elements in the analysis. A two-node beam element from LS-DYNA element library is used to model the tie bars in the concrete. The element formulation for the beam element is Hughes-Liu with cross-section integration. The reinforcement elements are embedded anywhere within the concrete elements. The strain in the tie bars is taken to be the same as the concrete in which full bond between the tie bars and surrounding concrete is assumed. The steel liner plate is modeled using four node shell element from the LS-DYNA element library. Belytschko-Tsay shell elements with five integration points through the thickness are used to model the shell behavior.

A minimum of eight elements is used through the concrete thickness of the wall. The element size is 12 in along length, and 6 in along height and thickness. A total of 270,000 elements are used for the model of the SC wall. Fixed boundary conditions are applied by restraining translations and rotations along the three orthogonal directions at the wall outer edges as shown in Figure 2(b).
MATERIAL PROPERTIES

The material for the liner plate is assumed to be ASTM A36 with 36 ksi yield stress. The material for the tie bars is assumed to be ASTM A496 Grade 60 with 70 ksi yield stress. The 120 day concrete cylindrical compressive strength is assumed to be 4 ksi. The tie bars and liner plates are modeled with *MAT_PLASTIC_KINEMATIC material from LS-DYNA material library and the concrete is modeled using *MAT_WINFRITH_CONCRETE material from LS-DYNA material library. The strength of the materials with rate effect including the Dynamic Impact Factor (DIF) is always higher than the design strength of the
material and hence increased the steel and concrete material strength and ductility properties according to NEI 07-13 (2009) are used in the finite element analysis.

A failure criterion for the steel is coupled with an element-kill algorithm available in LS-DYNA code that removes the damaged element from the model when the damage variable reaches the predetermined critical value. During steel coupon testing, strain can reach to a failure limit of 12% but in this analysis, limiting strain value for tie bar was reduced because the larger stress and strain concentrations can be induced at the locations of concrete cracks. For steel liner plate, a higher failure strain limit is assumed because of the biaxial loading effects and because the mesh refinement is typically not adequate in analysis of larger structures in capturing the high strain concentrations at the discontinuities of the cracks. A failure criteria for concrete elements is applied using a strain erosion algorithm (*MAT_ADD_EROSION option) available in LS-DYNA. This strain algorithm simulated concrete breakup due to spalling and scabbing. In this study, the erosion strain in both compression and tension is assumed to be same.

TIE BAR SPACING

The tie bars are mainly designed to resist out-of-plane shear. The maximum tie bar spacing is designed according to ACI 349 (2006). Shear reinforcement is sized in the entire wall using the beam action. For this paper, a tie bar of size 0.75 in diameter deformed bar is used in the analysis. Shear reinforcement has been conservatively provided at all locations of the SC Wall even in areas with very low out-of-plane shear demand.

IMPACTING AIRCRAFT MODEL REPRESENTATION WITH RIERA FORCE HISTORY CURVE

The impact load is applied on SC wall using a fictitious Riera total force history curve as shown in Figure 3. The scales of both axes have been removed for reasons of sensitivity. The load is applied as a pressure at the center of the wall over the area as shown in Figure 4. In this example, the loading up to 0.21 s is only applied to the fuselage circle and after this the wing load is also added to the fuselage load. At 0.23 s, the turbine load is also added to the fuselage and wing loads, and continued all these three loads together until reaching to the 0.29 s. The turbine load is terminated at 0.29 s and the wing load is terminated at 0.38 s, and after that only the fuselage load is continued until reaching the end of the analysis. All the loads are applied as time varying uniform pressures over the area indicated in Figure 4.
ANALYSIS RESULTS

The SC wall is analyzed in the full 3-D configuration and used different parameters which affecting the behavior of the wall. These parameters include thickness of the wall (36 in, 48 in, 66 in, 78 in and 96 in), thickness of the steel plate (0.5 in and 0.75 in) and diameter of tie bars (0.5 in and 0.75 in). The total load cases presented in this paper are shown in Table 1. The nomenclature of the SC wall properties for the analysis case 1 from the Table 1, 3ft_th_4ksi_0.5inL_17inS_Tie_0.75in_dia is explained as the concrete of 3ft (36 in) thick and 4 ksi initial strength, 0.5 in thick back and front liner plates, and tie bars of 17 in spacing and 0.75 in diameter. The nomenclatures for the remaining load cases are also similar. The wall with 3ft thick, 0.25 in liner and 0.5 in diameter tie bar has
failed early and hence the results with 0.5 in diameter tie bar are not presenting further. The analysis results for all cases are presented in below sections.

Table 1. Analysis Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Name</th>
<th>Concrete Thickness (in)</th>
<th>Liner Thickness (in)</th>
<th>Tie Bar diameter (in)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3ft_th_4ksi_0.5inL_17inS_Tie_0.75in_dia</td>
<td>36</td>
<td>0.5</td>
<td>0.75</td>
<td>Perforation occurred</td>
</tr>
<tr>
<td>2</td>
<td>4ft_th_4ksi_0.25inL_17inS_Tie_0.75in_dia</td>
<td>48</td>
<td>0.25</td>
<td>0.75</td>
<td>Perforation occurred</td>
</tr>
<tr>
<td>3</td>
<td>4ft_th_4ksi_0.5inL_17inS_Tie_0.75in_dia</td>
<td>48</td>
<td>0.5</td>
<td>0.75</td>
<td>Perforation occurred</td>
</tr>
<tr>
<td>4</td>
<td>4ft_th_4ksi_0.75inL_17inS_Tie_0.75in_dia</td>
<td>48</td>
<td>0.75</td>
<td>0.75</td>
<td>Perforation occurred</td>
</tr>
<tr>
<td>5</td>
<td>4ft_th_4ksi_1inL_17inS_Tie_0.75in_dia</td>
<td>48</td>
<td>1</td>
<td>0.75</td>
<td>Perforation occurred</td>
</tr>
<tr>
<td>6</td>
<td>5.5ft_th_4ksi_0.5inL_17inS_Tie_0.75in_dia</td>
<td>66</td>
<td>0.5</td>
<td>0.75</td>
<td>No Perforation</td>
</tr>
<tr>
<td>7</td>
<td>5.5ft_th_4ksi_1inL_17inS_Tie_0.75in_dia</td>
<td>66</td>
<td>1</td>
<td>0.75</td>
<td>No Perforation</td>
</tr>
<tr>
<td>8</td>
<td>6.5ft_th_4ksi_0.5inL_17inS_Tie_0.75in_dia</td>
<td>78</td>
<td>0.5</td>
<td>0.75</td>
<td>No Perforation</td>
</tr>
<tr>
<td>9</td>
<td>6.5ft_th_4ksi_1inL_17inS_Tie_0.75in_dia</td>
<td>78</td>
<td>1</td>
<td>0.75</td>
<td>No Perforation</td>
</tr>
<tr>
<td>10</td>
<td>8ft_th_4ksi_0.5inL_17inS_Tie_0.75in_dia</td>
<td>96</td>
<td>0.5</td>
<td>0.75</td>
<td>No Perforation</td>
</tr>
<tr>
<td>11</td>
<td>8ft_th_4ksi_1inL_17inS_Tie_0.75in_dia</td>
<td>96</td>
<td>1</td>
<td>0.75</td>
<td>No Perforation</td>
</tr>
</tbody>
</table>

CASE 1

(a) (b)

Figure 5. (a) Perforation in SC wall at 0.31 s (b) Crack pattern at 0.31 s

Results from the numerical simulation for Case 1 showed a perforation at 0.28 seconds. The analysis was stopped at 0.31 seconds and at this time the wall with punching type failure is shown in Figure 5(a). The crack pattern is shown in Figure 5(b). Cracking is extended over a fairly large area adjacent to the impact. The wall was failed just after wings hitting the wall. Because the wall did not resist the impact load, wall thickness has increased to 48” and conducted the subsequent analysis.
RESULTS from the numerical simulation for Case 2 showed a complete perforation with extensive damage to the wall at 0.29 seconds. The analysis was stopped at 0.38 seconds and at this time the wall with punching type failure is shown in Figure 6(a). The crack pattern is shown in Figure 6(b). Cracking is extended over a fairly large area adjacent to the impact. The wall was failed just after wings hitting the wall. Because the wall did not resist the impact load, the liner plate thickness has increased to 0.5 in, 0.75 in and 1 in and conducted the analysis in Case 3, Case 4 and Case 5 respectively. Even with increased liner plate thickness, the wall did not survive in Case 3, Case 4 and Case 5 and hence these results are not further presented in this paper. To resist the impact, the wall thickness was increased to 66”.

CASE 6

The structural response of the SC wall due to impact for Case 6 showed no perforation and liner plate is intact even with a minor spalling and scabbing of the concrete. The displacement time history of a node located on back face of the wall at the center of the impact area is shown in Figure 7(a). Figure 7(b) shows the contours for the maximum displacement and it is evident that the maximum displacement occurred at the location of the fuselage impacted location.

Figure 8(a) shows the high principal tensile strain at the region of the impact and cracking is likely to occur within the region of the high tensile strain as shown in Figure 8(b). Contours of the effective stress and plastic strain for liner plate at maximum deflection are shown in Figure 9(a) and Figure 9(b) respectively. Examining these figures shows that the steel liner plate has yielded. Contours of the effective stress and plastic strain for tie bars at maximum deflection are shown in Figure 10(a) and Figure 10(b) respectively. Examining these figures show that the tie bars are yielded and some elements are deleted by the erosion criteria (5% strain). Even though the wall resisted the intended impact, parametric study was conducted from Case 7 to Case 11 to improve wall’s behavior. It is because wall displacements
should be less to reduce cranes dislodge from supports and to reduce damage to inside utilities. Because of this reason and to know the SC wall behavior with different parameters, parametric study was conducted. To study the liner plate thickness effect in resisting the impact load, liner plate thickness is increased to 1 in and conducted the Case 7 analysis.

![Graph](image1)

**Figure 7.** (a) Displacement time history of a node located at the center of the back side of the wall (b) Maximum displacement contour at 0.49 s

![Graph](image2)

**Figure 8.** Concrete (a) principal tensile strain at peak displacement (b) crack pattern at peak displacement

![Graph](image3)

**Figure 9.** Steel line plate (a) von Mises stress at peak displacement (b) effective plastic strain at peak displacement
Figure 10. Tie bars (a) von Mises stress at peak displacement (b) effective plastic strain at peak displacement

CASE 7

The structural response of the SC wall due to impact for Case 7 showed no perforation and liner plate is intact even with a minor spalling and scabbing of the concrete. The displacement time history of a node located on back face of the wall at the center of the impact area is shown in Figure 11(a). It also showed the bounce back response of the wall with some residual deformation. Figure 11 (b) shows the contours for the maximum displacement and it is evident that the maximum displacement occurred at the location of the fuselage impacted location. In part of parametric study, wall thickness is increased to 78 in and conducted the Case 8 analysis.

CASE 8

The structural response of the SC wall due to impact for Case 8 showed no perforation and liner plate is intact even without any spalling and scabbing of the concrete. The displacement time history of a node located on back face of the wall at
the center of the impact area is shown in Figure 12(a). It also showed the bounce back response of the wall with some residual deformation. Figure 12 (b) shows the contours for the maximum displacement and it is evident that the maximum displacement occurred at the location of the fuselage impacted location. In part of parametric study, liner plate thickness is increased to 1 in and conducted the Case 9 analysis.

![Figure 12](image)

**Figure 12.** (a) Displacement time history of a node located at the center of the back side of the wall (b) Maximum displacement contour at 0.3 s

**CASE 9**

The structural response of the SC wall due to impact for Case 9 showed no perforation and liner plate is intact even without any spalling and scabbing of the concrete. The displacement time history of a node located on back face of the wall at the center of the impact area is shown in Figure 13(a). It also showed the bounce back response of the wall with some residual deformation. Figure 13 (b) shows the contours for the maximum displacement and it is evident that the maximum displacement occurred at the location of the fuselage impacted location. From this result, it is clear that there is not much advantage to increase the liner thickness for Case 8. In part of parametric study, wall thickness is increased to 96 in and conducted the Case 10 analysis.
CASE 10

The structural response of the SC wall due to impact for Case 10 showed no perforation and liner plate is intact even without any spalling and scabbing of the concrete. The displacement time history of a node located on back face of the wall at the center of the impact area is shown in Figure 14(a). It also showed the bounce back response of the wall with some residual deformation. Figure 14 (b) shows the contours for the maximum displacement and it is evident that the maximum displacement occurred at the location of the fuselage impacted location. In part of parametric study, liner plate thickness is increased to 1 in and conducted the Case 11 analysis.

CASE 11

The structural response of the SC wall due to impact for Case 11 showed no perforation and liner plate is intact even without any spalling and scabbing of the concrete. The displacement time history of a node located on back face of the wall at the center of the impact area is shown in Figure 14(a). It also showed the bounce back response of the wall with some residual deformation. Figure 14 (b) shows the contours for the maximum displacement and it is evident that the maximum displacement occurred at the location of the fuselage impacted location. In part of parametric study, liner plate thickness is increased to 1 in and conducted the Case 11 analysis.
the center of the impact area is shown in Figure 15(a). It also showed the bounce back response of the wall with some residual deformation. Figure 15 (b) shows the contours for the maximum displacement and it is evident that the maximum displacement occurred at the location of the fuselage impacted location. From this result, it is clear that there is not much advantage to increase the liner thickness for Case 10.

(a)      (b)

![Displacement time history of a node located at the center of the back side of the wall](image)

![Maximum displacement contour at 0.29 s](image)

**Figure 15.** (a) Displacement time history of a node located at the center of the back side of the wall (b) Maximum displacement contour at 0.29 s

**CONCLUSIONS**

This work represents a numerical study that aims at evaluating the effect of several parameters affecting the nonlinear behavior of SC walls with impact load. The damage and failure of a SC wall, subjected to impact load generated from a sample Riera force history has been studied with LS-DYNA using the Winfrith concrete model which covers all aspects of concrete behavior including cracking. The parameters of interest include the wall thickness, liner plate thickness, tie bar spacing and diameter. The thin walls are more effective in reducing the peak deformation by increasing the liner plate thickness comparing to thicker walls. Increasing the liner plate thickness increased the flexural behavior of the wall. Tie bars are also played an important role in which walls with less number of tie bars have potentially failed in complete shear around the central loaded area. Concrete crushing or cracking alone have not resulted the perforation but the significant rupture to tie bars and liner plates resulted the ultimate structural failure.

**REFERENCES**


