LS-DYNA MAT_159 MODEL FOR SIMULATING THE FAILURE OF CONCRETE STRUCTURES UNDER MISSILE IMPACT LOADING

Yuxin Liu[1], Jianming Cao[2], Xue Ming Han[3], Wei Liu[4]

[1]Senior Civil Engineer, Candu Energy Inc., Mississauga, Canada (yuxin.liu@candu.com)
[2]Civil Analyst, Dept. of Civil Engineering, Candu Energy Inc., Mississauga, Canada
[3]Director, Candu Energy Inc., Mississauga, Canada
[4]Manager, Dept. of Civil Engineering, Candu Energy Inc., Mississauga, Canada

ABSTRACT

To assess the failure effect of missile impact on reinforced concrete structures, tests have been carried out in the VTT research program, on which this study is to simulate the experimental results using LS-DYNA software. The *MAT_CSCM concrete failure model is used to simulate the VTT test results of concrete cylinder specimens. Then the failure model is applied to analyze the VTT concrete walls under soft missile impact loading. Finally, a parametric study is carried out to investigate the effect of impact velocity on maximum support rotations. It is shown that the analysis results have good agreement with the tested results of concrete cylinder specimens in both uniaxial unconfined and tri-axial confined conditions. The simulated maximum deflection of reinforced concrete square wall under soft missile impact loading is matched well with the experiment values. With the increase of impact velocity, the maximum deflection/rotation increases and the corresponding time, at which the maximal displacement occurs, is also increased. Using LS-DYNA can obtain much accurate maximum deflection of concrete wall structures under missile impact loading for structural integrity and failure assessment.

INTRODUCTION

Heavy and high speed commercial aircraft impact loadings are required to consider in designing nuclear power plants (RD-337, 2008; NEI 07-13, 2011). The VTT test program is to investigate the response behavior of reinforced and prestressed concrete walls under missile impact loading (OECD, 2011). Meanwhile, much research has been done to compare the analyzed results with the experimental results in the IRIS program (Orbovic et al, 2011). This paper is to continue the research on numerical simulation using LS-DYNA (Hallquist, 2007) to predict the response of reinforced concrete walls subjected to soft missile impact loading. The LS-DYNA concrete failure model *MAT-CSCM (shorted as M_159 hereafter) is calibrated using the test data and then the model is applied to analyze the concrete walls impacted by soft missiles.The simulated results will be compared with those from VTT experiments (OECD, 2011).

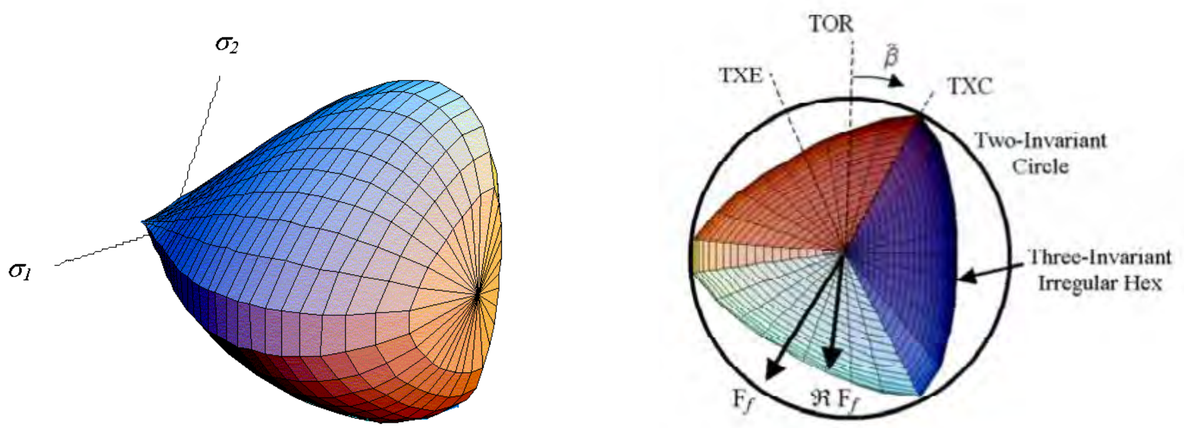
In this study, the LS-DYNA damage model *Mat_84/85 (M_84 hereafter) is compared with M_159 using the VTT tested results of cylindrical specimens. A LS-DYNA model with a single cubic element is analyzed first, and then a model having 768 elements is analyzed with considering the effect of confinement of the cylindrical specimens. The calibrated LS-DYNA M_159 was applied to the reinforced concrete walls with dimensions 2.0×2.0×0.15 m subjected to soft missile impact loading. The simulated displacement-time histories are compared with those from VTT experiments. Parametric study is also performed to investigate the influence of missile impact velocity on support rotations of reinforced concrete walls. It is found from the simulation results that LS-DYNA analysis results show good agreement with the test results of concrete cylinder specimens in both uniaxial unconfined and tri-axial confined conditions. The simulated maximum deflection for the concrete square wall under soft missile impact loading has a good agreement with the test result. However, after about the end of missile striking, the tested and simulated results are not perfectly matched likely due to the effects of cumulative errors in modelling, simulation of stress-strain constitutive relation, etc. Further investigation on applying LS-DYNA with concrete damage model is needed to improve the numerical simulation.

CALIBRATION OF CONCRETE DAMAGE MODEL

To simulate the response behavior concrete walls subjected to missile impact loading, the VTT experimental results of cylindrical concrete specimens are simulated using LS-DYNA program. This section focuses on the calibration of concrete damage model M_159 using the VTT test results.

M_159 Concrete Model

In LS-DYNA, the M_159 concrete failure surface is defined in terms of the first invariant stress tensor I_1, shear failure surface F_f, Rubin third-invariant reduction factor $\Re$, and the hardening cap F_c function (DOT, 2007). The failure surface is curve-fitted to the experimental data. Figure 1(a) shows the failure surface in the principal-stress coordinate system, and a deviatoric plane is shown in Figure 1(b). The physical meaning is that there no failure occurrence within the surface; but stiffness and strength will degrade outside the surface.



(a) Failure surface (b) Three-invariant shapes

Figure 1. Illustration of M_159 concrete failure model.

In addition to the failure surface, an initial yield stress surface is determined through scaling the failure surface by a factor ranging between $0.7 < NH \leq 1$, which governs the location of the initial yield surface. When NH=1, no initial yield is considered. If the stress state goes beyond the failure surface, concrete strength is reduced by a scalar factor d ranging from 0 to 1, which is defined by max principal strain for brittle failure and strain energy for ductile failure. Each element stress component will be reduced by (1-d). As $d \rightarrow 1$, an element loses all strength and stiffness. An element erodes when $d > 0.99$ and the maximum principal strain is greater than a specified input value. The M_159 model also takes strain-rate effect and element mesh size sensitivity into account.

M_159 Model Input Parameters for VTT Cylindrical Specimens

For simulating the cylinder concrete specimens using LS-DYNA, the material properties are based on the VTT tested uniaxial and triaxial results as shown in Table 1. One unconfined specimen, and four confined specimens with pressures 15.5MPa, 26MPa, 47MPa, and 100MPa are considered in the simulation. The M_159 concrete material model has up to 37 input parameters, with a minimum of 19 parameters that must be fit to data. There are two types of inputs: short and long formats. In the short input format, only the mass density, unconfined compression strength, and max aggregate size (19 mm) are input.

Table 1: Concrete property for model calibration.

Property	Unconfined	Confined
Mass Density ρ (kg/m^3)	22610	22610
Compression Strength f_c' (MPa)	69.0	66.93
Young's Modulus E_c (MPa)	29663	29670
Poisson Ratio υ	0.22	0.223

In long input format, the α, β, λ, and θ values for the tri-axial compression (TXC), torsion (TOR), and tri-axial extension (TXE) are estimated using the regression expression in the manual (DOT, 2007) as shown in Table 2, where the parameters with strength 62.7 MPa are also given for the concrete wall under missile impact. The corresponding concrete Young's modulus is used to determine the shear and bulk moduli. The hardening and softening parameters are adjusted to match with the experimental results.

Table 2: Input parameters for failure surface.

Surface	Input P	A_P	B_P	C_P	69.0MPa	66.93MPa	62.7MPa
TXC	α (MPa)	-0.003	0.316975	7.7047	15.29295	15.48094	15.78514
	λ (MPa)	0	0	10.5	10.5	10.5	10.5
	β (1/MPa)	0	0	1.93E-02	0.01929	0.01929	0.01929
	θ	1.32E-05	2.35E-03	0.214006	0.439408	0.430815	0.413608
TOR	α_1	0	0	0.74735	0.74735	0.74735	0.74735
	λ_1	0	0	0.17	0.17	0.17	0.17
	β_1(1/MPa)	-2.00E-05	2.27E-04	8.17E-02	0.002293	0.007444	0.017437
	θ_1 (1/MPa)	-4.09E-07	-1.06E-06	1.55E-03	-0.00047	-0.00035	-0.00012
TXE	α_2	0	0	0.66	0.66	0.66	0.66
	λ_2	0	0	0.16	0.16	0.16	0.16
	β_2 (1/MPa)	-2.00E-05	2.27E-04	8.27E-02	0.003293	0.008444	0.018437
	θ_2 (1/MPa)	-4.87E-07	-1.89E-06	1.88E-03	-0.00057	-0.00043	-0.00015

Results for a Single LS-DYNA Element Model

To simulate the actual cylinder concrete specimens, a single LS-DYNA cubic element model with material properties in Table 1 is considered first to compare the LS-DYNA concrete damage models. The LS-DYNA damage modes, M_84 and M_159 were selected for comparison. For M_159 model, the short input format with *MAT_CSCM_CONCRETE is designated as 159A, where the values of most parameters are embedded in the LS-DYNA program. The long input format with *MAT_CSCM (159B) allows the users to input their own parameters.

The single cubic element model with 1 inch side length shown in Figure 2 is applied to simulate the uniaxial and triaxial concrete test results. According to stress-stain relationship in Figure 2, using M_84 yields the purple curve (designated as 84) with a peak response of 77 MPa, which is 11.6% higher than 69MPa. In this case the material softening effect is not simulated well because the straight line is going forever. For the short, the response curve is the black curve (159A), and the long input yields the blue curve (159B), which is closer to the tested curve in red. Thus, the long parameter input for *MAT_CSCM (159B) with different softening parameters is applied for the further analyses.

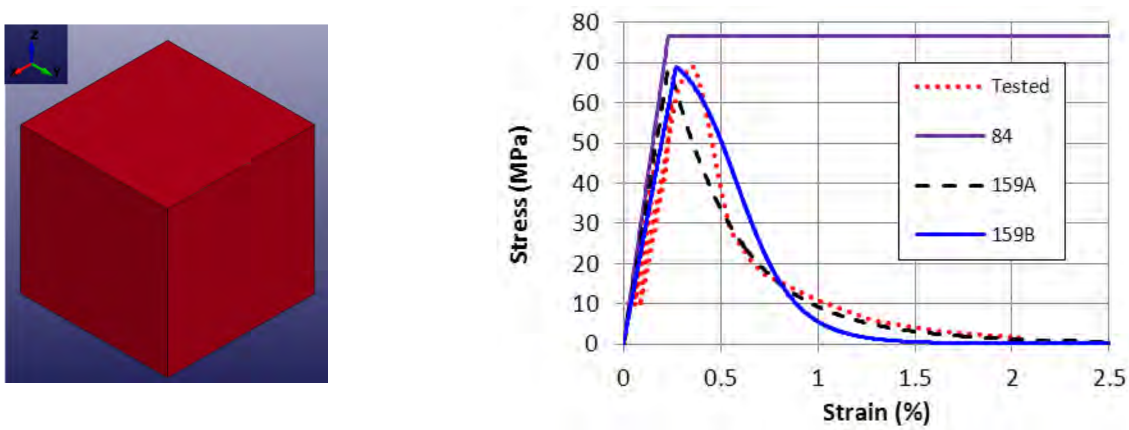
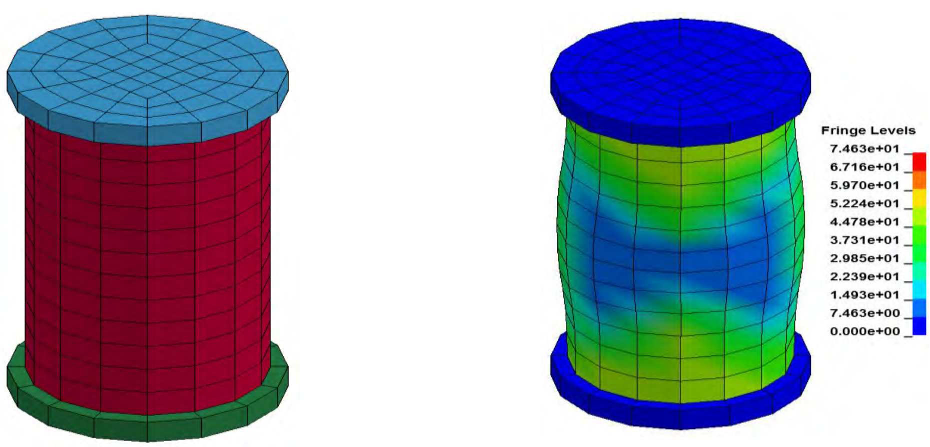


Figure 2. Calculated axial stress-strain curve of cubic specimen (unconfined).

Results for the Cylindrical Concrete Specimens

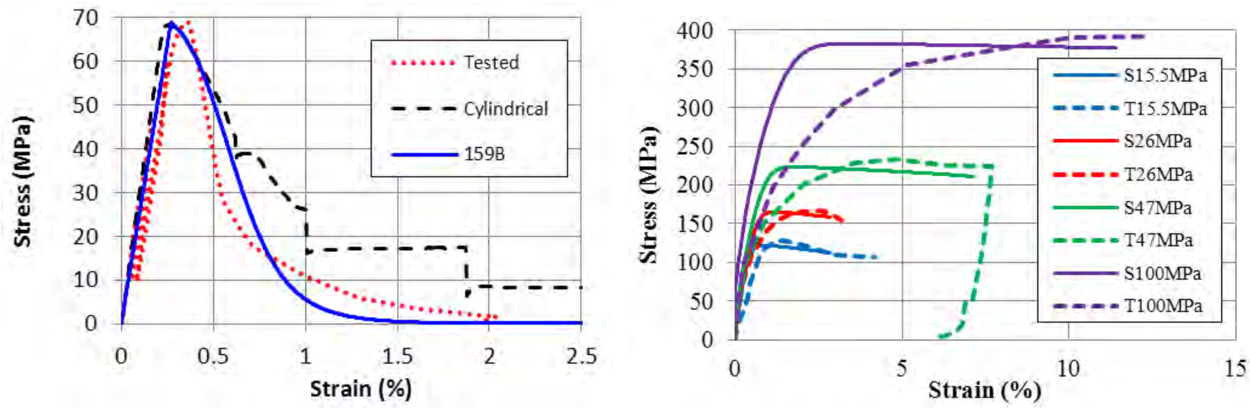
Based on the analysis results shown in Figure 2, the LS-DYNA concrete damage model *MAT_CSCM (159B) is applied to simulate each VTT concrete cylinder specimens. Figure 3(a) shows a model having total 768 elements to simulate the cylinder specimens. The contact surface between each end caps is modeled using contact type *CONTACT_CONSTRAINT_NODES_TO_SURFACE with coefficient of friction of 0.3. The cylinder is loaded in compression by applying a constant axial velocity to the layer of nodes along the top end cap. While the bottom end cap is constrained from motion and rotation along the layer of end cap nodes.



(a) Finite element model (b) A stress state after compression

Figure 3. Concrete cylinder model with end caps and stress response.

Figure 3(b) shows the stress distribution in a loading state. Calculated stress-strain relationship of cylinder surface under unconfined compression together with test result is shown in Figure 4(a). The solid response curve in black is quite close to the test result around the peak region, but when the strain exceeds about 0.5%, the stress does not approach to zero. Meanwhile, it is observed that the simulated response curve is not smoothed because of the strength and stiffness degradation of some elements. It is expected that when the element mesh is refined the curve will be smoothed.



(a) Confined condition (b) Comparison

Figure 4. Concrete cylinder surface stress-strain relationships.

When the concrete specimens are confined, the stress-strain curves are shown in Figure 4(b), where the dashed curves represent the tested results, and the solid curves for simulated results. For instance, S15.5MPa means the simulated result of the cylindrical specimen with confined pressure of 15.5 MPa, while the T15.5MPa means the corresponding tested result. It is observed that for the same model, the response curves with confinement are smoothed. The simulated curves have the same variation trend as the corresponding tested curves.

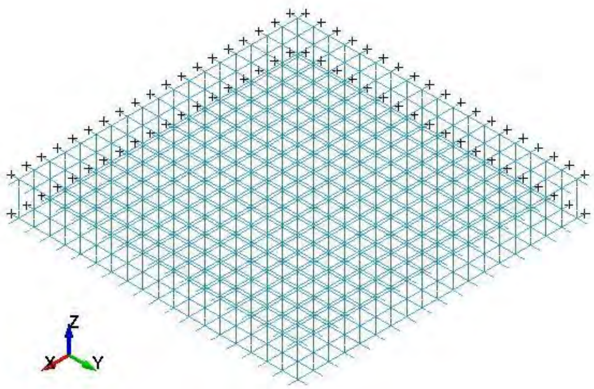
SIMULATION OF REINFORCED CONCRETE WALL

Modelling of Concrete Wall

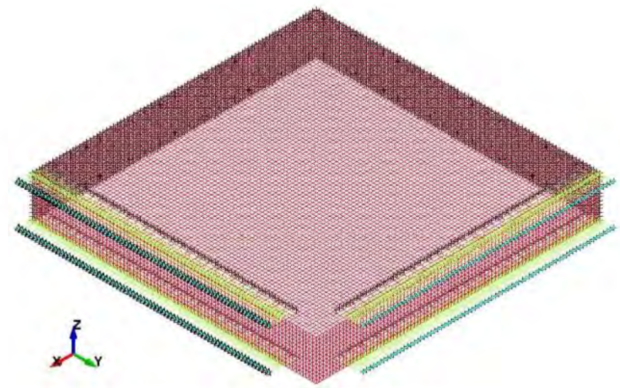
Material properties from the cylindrical specimens for the square walls are similar to those values in Table 1. Material properties for steel reinforcement bars have mass density 7,850 kg/m^3, yield strength 600 MPa, and Young's modulus 200 GPa. For the impact testing, the missile consists of two part materials. The steel material properties of the missile bars have mass density 8,000 kg/m^{3}and yield strength 300 MPa. These concrete and steel parameters used in the simulations. A long input of concrete material parameters is adopted and the parameters in Table are input in the concrete failure model *MAT_CSCM.

The LS-DYNA *CONTACT_AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE is used to simulate the contact. The missile represents the slave part and the target concrete wall with steel reinforcement represents the master parts. The one-way contact is chosen as it is computationally more efficient since it has close to half the cost of the two-way treatment.

A 3-D finite element model is developed to simulate the reinforced concrete target wall with dimensions 1.05×1.05×0.15 m of a quarter of the concrete wall cover 15 mm. Figure 5(a) shows the steel reinforcement in horizontal and vertical directions. For each rebar at the symmetrical plane, only the vertical translation is allowed. Figure 5(b) shows the concrete wall with support conditions. The supporting system is modelled upon using the arrangement provided in the program document. In the symmetrical plane, the translation displacement perpendicular to the plane is constrained at support edges, and the vertical displacement is free at non-support edges. Supports along the top and bottom surface are restrained rigidly restrained in vertical direction, while elastic springs are used to simulate the horizontal supports.



(a) Steel reinforcement



(b) Wall with supports

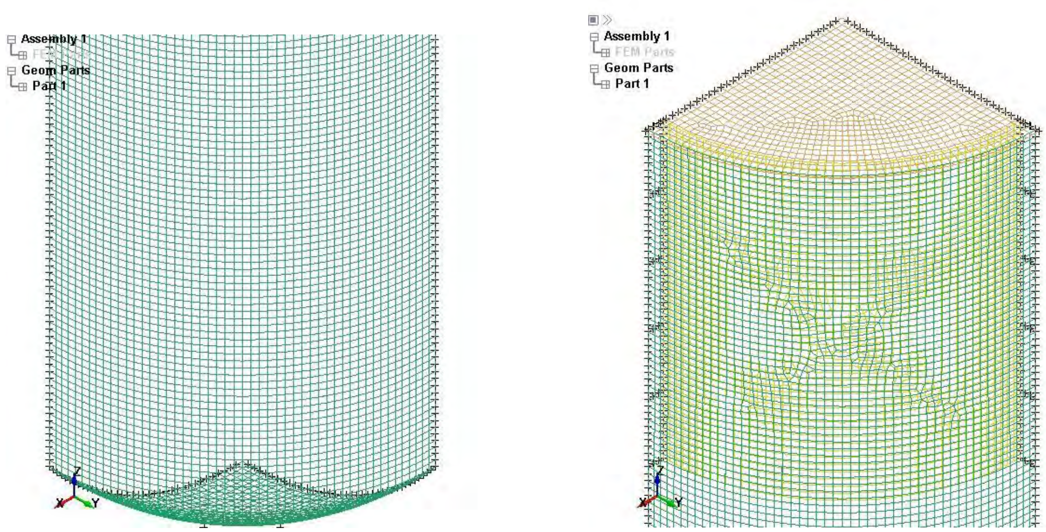
Figure 5. Analysis model to simulate missile impact.

The model includes about 90847 elements, among which total solid elements for concrete wall are 84672 and total beam elements for reinforcement steel are 6175. Concrete wall is modelled using constant stress SOLID (brick) element (ELFORM = 1) with mesh size 12.5×12.5×12.5 mm (12 elements through the concrete wall thickness). This mesh size is chosen based on comprehensive mesh discretization sensitivity analysis using four different mesh sizes. Reinforcement rebars are modelled using BEAM (Truss) elements (ELFORM =3) with a mesh size 18.3 mm (Figure 5(a)). The diameter of longitudinal horizontal and vertical rebars at the front and rear faces is 6 mm with a total number of rebars in each direction per each face 38 bars. The transverse rebars of 4.41 mm diameter are modeled with total density of 50.1 cm^2/m^2. The nodes of the longitudinal and transverse reinforcement rebars are coupled to the nodes of the concrete wall through *CONSTRAINED_LAGRANGE_IN_SOLID keyword.

Since the constitutive model M_159 has been used to simulate the concrete cylindrical specimens, this model will be applied to simulate the concrete wall. For steel reinforcement, the constitutive material model *MAT_PLASTIC_KINEMATIC is used. Concrete elements are removed from the calculation when element stress damage index exceeds 0.99 (full damage is 1.0) and the maximum principal strain exceeds 5% by setting ERODE=1.05 in the concrete model. This erosion criterion is chosen based on comprehensive sensitivity analysis report from LS-DYNA.

Modelling of Soft Missile

A 3-D finite element model is developed for a quarter of the missile, and the nose mesh is shown in Figure 6(a), and tail mesh in Figure 6(b). The model includes about 29730 elements, among which shell elements for the stainless steel pipe and the rear carbon steel pipe and plate, and beam elements for the screws connecting carbon steel pipe to the stainless steel pipe. The stainless steel parts of the missile as well as the rear plates and the carbon steel pipe are modelled using SHELL elements with mesh size of 4.0 mm. The carbon steel pipe is connected to the stainless steel pipe using 6 bolts along the length of the steel pipe every quarter of the perimeter. The bolts are modelled using BEAM (truss) elements. The constitutive material model *MAT_PIECEWISE_LINEAR_PLASTICITY is used for the stainless steel pipe, in which the stress-strain curve is obtained from stainless steel test. The constitutive material model used to model the other parts of the missile is *MAT_PLASTIC_KINEMATIC except the stainless steel. Strain rate effect is not included in modelling the missile.

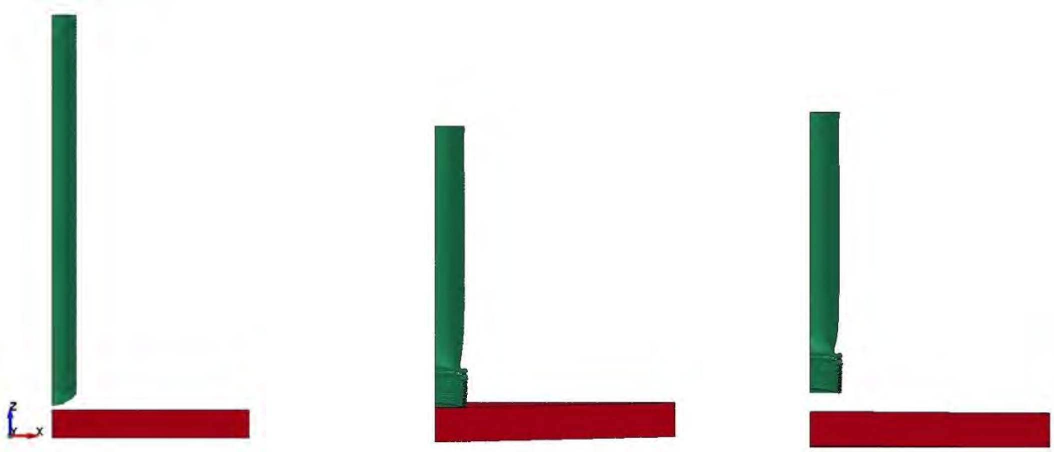


(a) Mesh of nose (b) Mesh of tail

Figure 6. Modelling of the soft missile.

Analysis Results

This subsection presents the simulation results of the reinforced concrete wall tested in the VTT program. Both M_159 and M_84 concrete failure models are applied in the analyses with time step of 3.10×10^{-4} ms. A total elapsed running time is around 20 Hrs for a period of 100 ms for the quarter model. Figure 7(a) shows the missile-target before impact loading; (b) and (c) show the response.



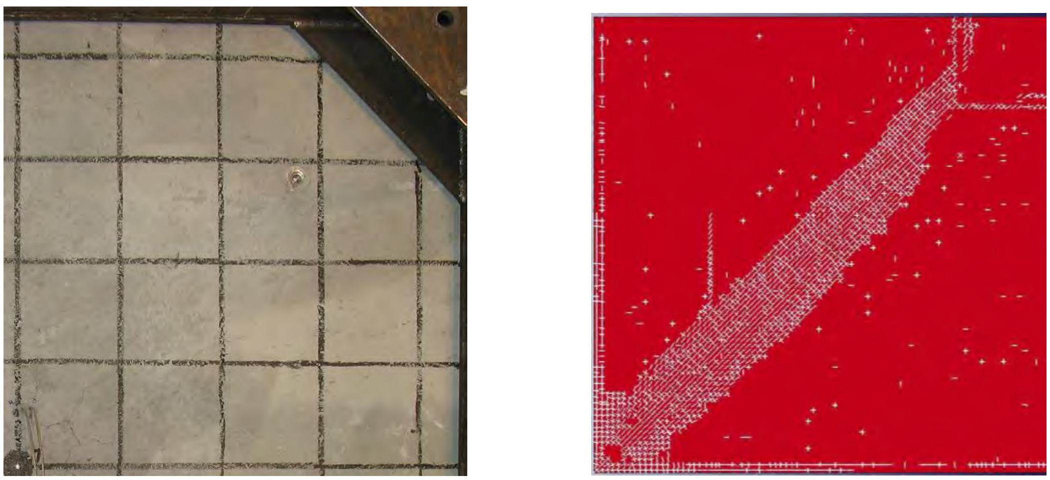
(a) Before Impact (b) At 16 ms (c) At 30 ms

Figure 7. Response of missile and wall

It is seen from Figure 7(b) that the missile damage is in a buckling failure mode. At about 16.5 ms, the missile reached its maximum deformation of 889 mm and then starts to rebound till the contact between target and missile completely diminishes. After rebounding, the missile moves in the opposite directions and it does not re-hit the concrete wall as shown in Figure 7(c). The concrete wall experiences deformation, and after rebounding, the deformed missile moves back and the wall restores to its original position with some residual deformation.

Comparison with Experimental Results

After missile imapct loading test, the concrete wall expierienced slight cracking along the diagonal direction observed on the back surface as shown in Figure 8(a). As LS_DYNA analysis with using M_84 is carried out, the cracking pattern on the back face is shown in Figure 8(b), which is consuistent with the failure pattern shown on the tested specimen.

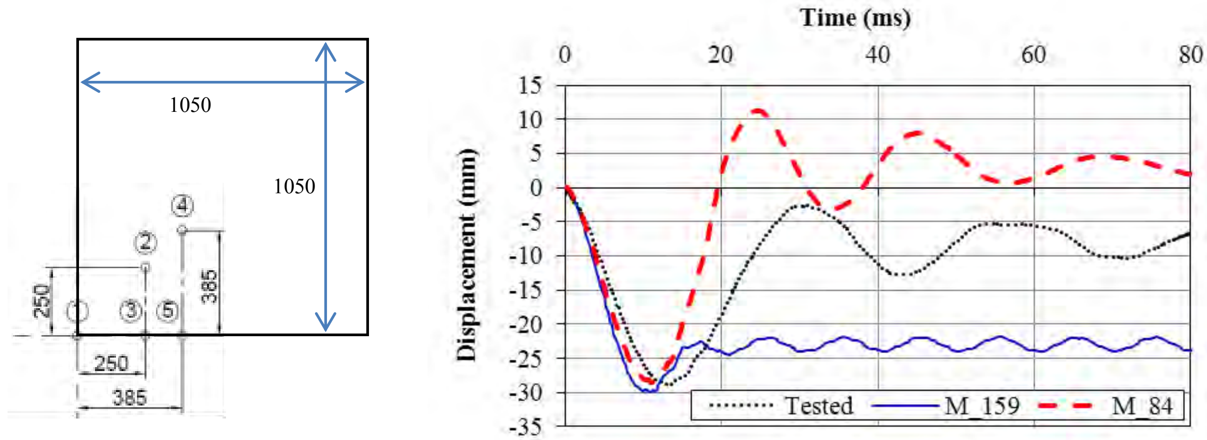


(a) Tested wall (b) Simulated cracking pattern

Figure 8. Failure pattern on back face of the concrete wall.

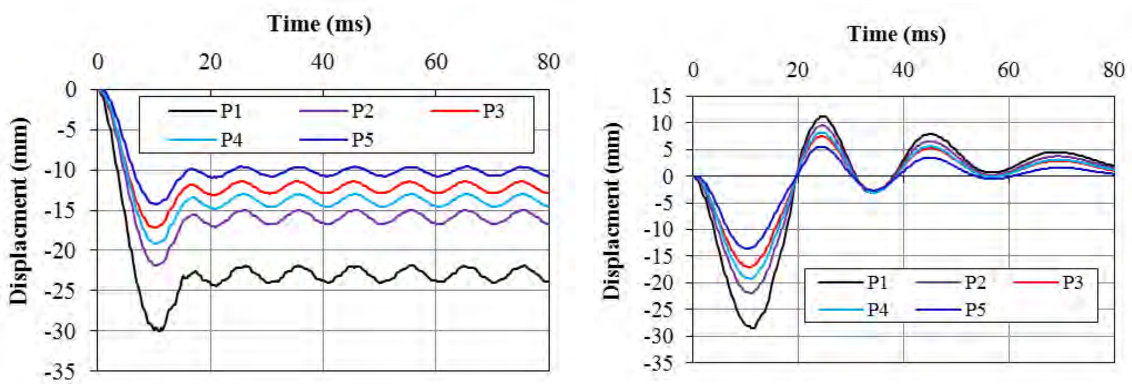
To compare with the test results, the displacment at central point ① (P1) shown in Figure 9(a) is considered as maximum deflection occurs at this location. The curves from the LS-DYNA analyses based cocnrete failure models M_84 and M_159 are shown in Figure 9(b); while the dotted black cure is from the VTT test. It is seen by comparing with the experimental results that, using M_84 concrete failure model can yield better results than using M _159 in this specific example. Both concrete failure models can yield the maximum displacements that are quite close to the maximum displacement from experiment. During the free vibration after the end at about 17 ms of missile impact, compared to M_159 cure, the M_84 cure has vibration nature closer to the tested curve.

For all 5 measured points P1 to P5 shown in Figure 9(a), the displacement time histories on the rear face of wall are shown in Figure 10. Figure 10(a) shows the time-displacement histories obtained using LS-DYNA material model M_159. It is seen that, M_159 model over predicts the damage because the residual displacement is too large. Even though 10% damping is set for the concrete material and 6% damping to the steel reinforcement, the displacement does not decay in the range of free vibration. Figure 10(b) shows the time-displacement histories obtained using LS-DYNA material model M_84. It is seen in this case that, this concrete failure model can correctly simulate the damping effect during and after the missile impact loading and the damped decaying vibration is simulated well. But in this case, the M_84 model seems to underestimate the damage of concrete wall because nearly no residual deformation occurs.



(a) Measured at 5 points (b) Displacement response

Figure 9. Displacement-time history on the rear face of the concrete wall.



(a) Using M_159 (b) Using M_84

Figure 10. Displacement-time history on the rear face of concrete wall.

Parametric Study

In light of the comparison study in the previous subsection, *MAT_84 model is better to be used for predicting the behaviour of concrete wall under missile impact. Using this failure model, a parametric study is performed in the following to investigate the effect of reinforcing and impact velocity on the response of support rotations. The concrete wall model developed in the previous subsection is applied but the impact velocity varies as shown in Table 3. After LS-DYNA runs through using M_84, the maximum displacement d_{max} at the centre (P1) of the concrete wall is summarized in Table 3. It is observed that increasing impact velocity leads to the increase of maximum deflection response, and the time, at which the maximum deflection occurs, is also increased.

To assess the failure in flexure due to impactive loading, the current design standard (CSA 287.3, 1993) requires checking support rotation. For reinforced concrete members, such rotation should be less than 4°. For the reinforced concrete walls under consideration, the corresponding support rotation can be defined as

$$\theta = \tan^{-1}(d_{max} / L) \tag{1}$$

where L=1000 mm, is half the side length of concrete wall. Substituting the maximum deflection values in Table 3 into Equation (1) yields the corresponding rotations, which are also given in Table 3. When the impact velocity increases, the maximum rotation increases. For impact velocity of 110 m/s, the support rotation is about 2°, and as the impact velocity is increased to 150 m/s, the support rotation is about 4°.

Table 3: Maximum deflection and support rotation.

V_i (m/s)	t_{max} (ms)	d_{max} (mm)	θ (°)
60	10.25	11.25	0.64
110	11.75	28.58	1.66
150	13.5	67.71	3.87

SUMMARY AND CONCLUSIONS

This paper presents the results of the LS-DYNA simulations for cylindrical concrete specimens with and without confined pressure using LS-DYNA, and then a quarter model of a square concrete wall is developed to simulate the behaviour of reinforced concrete wall under soft missile impact. It is shown that, a reasonable agreement with the experimental results of the concrete cylinder specimens are achieved using the single cubic model and the cylindrical model. When the LS-DYNA M_159 and M_84 damage models are applied to the wall under soft-missile impact, both failure models can yield the maximum deflections that are close to the test results. But after the end of missile striking, the simulated results in the free vibration stage are not well matched with the test results. It is also observed that M_84 model can lead to better results for the specific example compared to M_159. Parametric analysis shows that with the increase of impact velocity the maximum displacement or rotation is increased. Although LS-DYNA can be applied to predict much accurate maximum displacement of concrete walls under soft missile impact loading, further research is needed to improve the simulation to effectively capture the concrete behaviour of hardening, softening, and failure mechanism.

REFERENCES

CSA N287.3. (1993). *Design requirements for concrete containment structures for CANDU nuclear power plants*. Canadian Standards Association, Mississauga, Canada.

DOT. (2007). *Users Manual for LS-DYNA Concrete Material Model 159*, Publication No. FHWA-HRT-05-062. Department of Transportation, USA.

Hallquist, J. O. (2007). *LS-DYNA Keyword User's Manual Version 971*. Livermore Software Technology Corporation, California, USA.

OECD. (2011). *Improving Robustness Assessment Methodologies for Structures Impacted by Missiles* (IRIS_2010), Organisation for Economic Co-operation and Development, Nuclear Energy Agency.

NEI 07-13. (2011). *Methodology for Performing Aircraft Impact Assessments for New Plant Designs,* Revision 8P. ERIN Engineering & Research, Walnut Creek, California, USA.

Orbovic, N., F. Benboudjema, Y. Berthaud, .J-B. Colliat, F. Tarallo and J.-M. Rambach. “IRIS_2010 - Part III: Numerical Simulations of Meppen II-4 Test and VTT-IRSN-CNSC Punching Tests,” *Transactions, SMiRT 21*, Div-V: Paper ID# 163, New Delhi, India, 6-11 November, 2011.

RD-337. *Design of New Nuclear Power Plants*, Canadian Nuclear Safety Commission, November, 2008.