Simulation of Masonry Wall Failure and Debris Scatter

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ABSTRACT:

This paper outlines a methodology for the simulation of masonry wall failure and debris scatter. The aim of this work is to develop simulation techniques which can be used to assess and improve the design of building structures subject to high explosive loading. Masonry walls are constructed from bricks that are modelled as individual parts with tiebreak and single surface contact types.

A key requirement of this work is to accurately predict the final landing position and scatter pattern of any bricks. If the acceleration of a separated brick is significantly high, the trajectory and final landing position of the brick will be influenced by air-drag. In this work we simulate the air-drag force using a user FORTRAN subroutine and demonstrate its accuracy with comparison to theory.

The strength of the mortar-masonry brick bond is validated by comparison with laboratory experiments conducted in previous work showing close agreement. A series of simulations are then presented which demonstrate the failure and debris scatter of a simplified building structure.

Keywords:

Blast modelling, Masonry bricks, Tiebreak contact, Single-surface contact, Drag

INTRODUCTION

The aim of this work is to develop simulation techniques within LS-DYNA which can be used to assess and improve the design of building structures subject to high explosive loading. In this study masonry walls are constructed from bricks that are modelled as individual parts with tiebreak and single surface contact types [1]. The tiebreak contact is used to define the strength of the brick-mortar bond and is based on normal and shear strength failure parameters. A particular concern of masonry wall failure under blast loading is debris scatter which can cause secondary and tertiary injuries to occupants and pedestrians [2]. Therefore it is a key requirement of this work to accurately predict the final landing position and scatter pattern of bricks. If the acceleration of a separated brick is significantly high the trajectory and final landing position of the brick will be influenced by air-drag. In this work the air-drag force is simulated using a user FORTRAN subroutine.

This paper outlines a methodology for the simulation of masonry wall failure and debris scatter. The methodology used to simulate brick-mortar bond strength is presented in the first section. This is followed with a description of the software FE-WALL which is used to automatically generate wall structures. The implementation of the tiebreak contact and the strength of the brick-mortar bond are then validated by comparison with laboratory experiments conducted in previous work. The implementation of the air-drag subroutine is then validated with comparison to theory. In the final section a series of simulations are presented which demonstrate the failure and debris scatter of a simplified building structure. The simulations presented in this paper were performed on a HP Workstation with a 3.6GHz CPU and 2GB RAM using LS-DYNA 970 SMP rev. 6763.374 (5/19/2006) [1]. The simulation results are presented in SI units: N, m, kg, s.

MODELLING METHODOLOGY

In this study masonry walls are constructed from bricks that are modelled as individual parts with tiebreak and single surface contact types. The tiebreak contact is used to define the strength of the mortar between adjacent bricks and is based on normal and shear strength failure parameters [1]. The single surface contact is then used to model the interaction of bricks which are separated from the wall [1]. This final contact type is not associated with any failure criteria but is used to model the interaction of individual bricks, i.e. the user does not need to specify contact segments since all faces of the brick(s) are potential contact surfaces.

FE-WALL SOFTWARE

The software program FE-WALL was written to reduce the significant pre-processing time currently required to generate masonry wall structures using traditional pre-processing software, e.g. a single wall (5m x 3m) consists of approximately 880 standard masonry bricks and may include contact segments for each brick. FE-WALL generates an LS-DYNA specific ASCII file that defines the structure of a wall. A typical example showing the output of FE-WALL is shown in Figure 1.

The software allows a user to set the number of bricks, brick dimensions and number of elements per brick. The nodes, elements and contact segments are then calculated automatically by the software. In use the software can generate a 5m x 3m wall (4 x 2 x 2 elements per brick) with contact segments in < 1min. During this current project, additional features were added to the software including a method to simulate air-drag on bricks and brick splitting that allows the fractured surface to be colour coded for improved clarity.

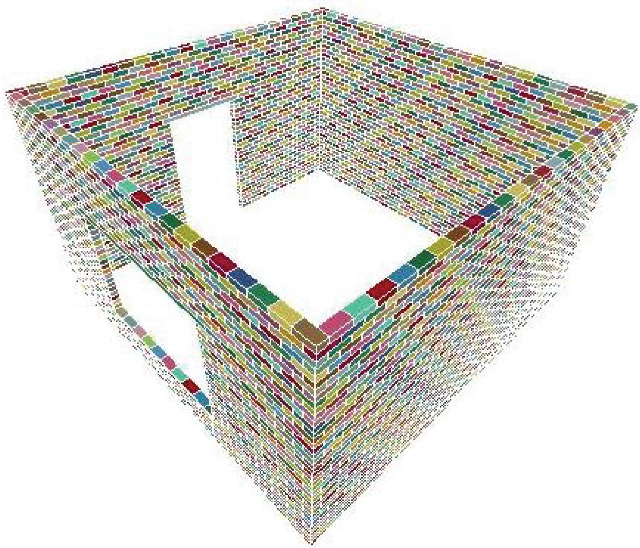


Figure 1: Typical output from FE-WALL software with roof removed for clarity. Model consists of approximately 3000 individual brick parts.

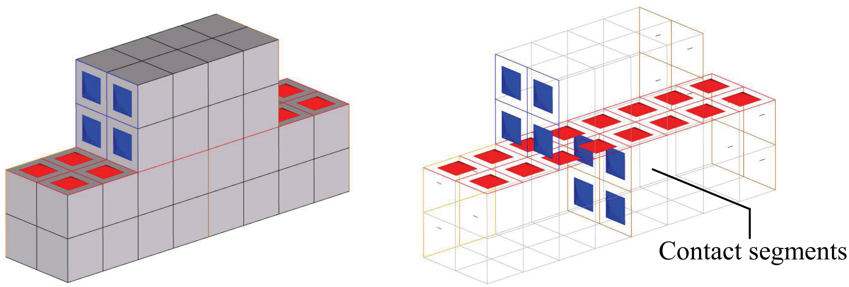


Figure 2: Image showing a subset of bricks with contacts segments (tiebreak) generated automatically with FE-WALL software.

An image showing the orientation of contact segments for a subset of bricks is presented in Figure 2.

The principle features of the FE-WALL software are summarised below:

- Automatic generation of wall structures for bricks and concrete blocks of arbitrary size.
- Contact segments are pre-defined and automatically exported with elements defining the wall.
- Simulation of air-drag for bricks allowing the user to modify the drag coefficient, cross-sectional area of the brick and air density.
- Includes brick splitting with coloured fractured surfaces to aid visualization

All the necessary keyword commands are generated automatically allowing the user to use the output file generated by FE-WALL in LS-DYNA simulations.

MODELLING THE BRICK-MORTAR BOND

The tiebreak contact type is used to model the strength of the brick-mortar bond and is based on normal and shear strength failure parameters [1]. The expression solved is:

$$\left(\frac{|\sigma_n|}{\text{NFLS}}\right)^2 + \left(\frac{|\sigma_s|}{\text{SFLS}}\right)^2 \geq 1\,, \qquad \text{(Eq.1)}$$

where σ_n is the normal tensile stress, σ_s is the shear stress, NFLS is the tensile failure stress and SFLS is the shear failure stress. After failure this contact type behaves as a surface-to-surface contact with no thickness offsets. The failure parameters used in the present work were obtained from a series of laboratory experiments performed by Liverpool University [3].

The masonry brick was simulated using a rigid material model. The application of this material model reduced the run-time of the computation compared to using a linear elastic material model by approximately thirty two times during a series of single wall blast studies.

MODEL SETUP

After defining the strength of the brick-mortar bond the user will need to apply boundary conditions and loads in the model including: single point boundary constraints, gravity, dynamic relaxation (used to model the initial relaxation of the wall under gravity) and segment pressure. As a first approximation the detonation of an explosive charge and the consequent loading pressure is determined from the load blast function within LS-DYNA called ConWep [1]. This is a semi-empirical expression developed by Kingery and Bulmash [4] and implemented by Rander-Pehrson and Bannister [5] that accounts for the angle of incidence but not reflections or shadowing effects. The blast loading can also be simulated using one of the following methods:

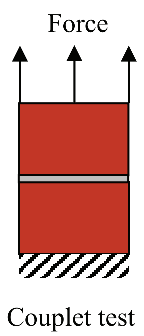
- ALE with FSI combined with an EOS for the explosive material, e.g. JWL
- Implementation of pressure load curves from specific experiments

SIMULATION RESULTS

In this section a series of simulations are presented to validate the implementation of the tiebreak contact for masonry wall failure. Simulation results are then presented showing the accuracy of the air-drag subroutine when compared with theory. In the final section a series of simulations are presented which demonstrate the failure and debris scatter of a simplified building structure.

VALIDATION OF THE BRICK-MORTAR BOND

The implementation of the tiebreak contact is validated by comparing the results of LS-DYNA simulations to two laboratory scale experiments (Couplet and Triplet) performed by the University of Liverpool [3]. The bricks used were Nori Class B engineering bricks with a mortar mix of 1:1:6 (by volume) prepared in accordance with BS 5628 (1978). The couplet test is a simple method to measure the tensile strength of the brick-mortar bond, Figure 3. The setup consisted of two half bricks measuring 0.1 x 0.065 x 0.1m bonded together, one on top of another with a 10mm thick mortar join. The bottom brick was constrained to a base while a tensile force was applied to the second brick. Two loading rates were considered including 100 kN/s and 1000 kN/s; however, due to the similarity in the results only the results for 1000 kN/s are presented. The simulation results are presented in Table 1 for a brick with 5 x 5 x 5 elements, showing close agreement with the experimental results.



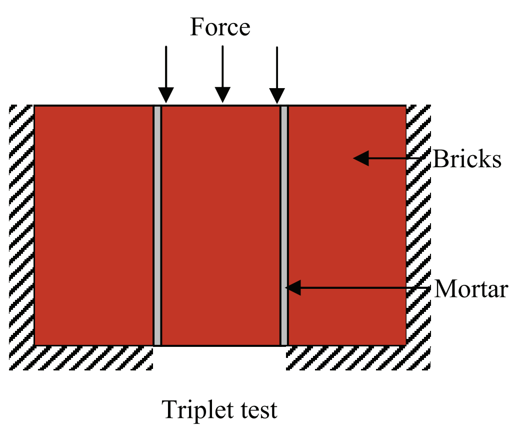


Figure 3: Images showing the setup of the couplet (left) and triplet (right) tests

A similar series of simulations were performed for the triplet test to measure the shear strength of the brick-mortar bond. The setup for this test consisted of three full length standard bricks measuring 0.225 x 0.075 x 0.1125m placed side by side, with the major length of the brick aligned in the vertical direction. A 10mm thick mortar join was applied between the middle-left and middle-right bricks. The left and right bricks were constrained on the bottom and side faces. A downward vertical compressive force was then applied to the middle brick. The failure of the tiebreak contact occurred when the shear strength failure criteria was reached. The motion of the brick is then constrained by the friction between the adjacent bricks. The simulation results are presented in Table 1 for a brick with 5 x 5 x 5 elements, showing close agreement with the experimental results.

Table 1 : Simulation results compared to couplet and triplet tests

Test	Failure force (N)	% diff. vs. exp
Couplet	3.76E+03	1
Triplet	1.19E+04	-1

The mesh density chosen for subsequent analysis was based on an element distribution of 4 x 2 x 2. This mesh density was chosen from a series of mesh sensitivity studies as it provided the best balance between accuracy and low simulation run-times.

MODELLING THE AIR DRAG OF BRICKS

A key requirement of this work is to predict the final landing position and scatter pattern of bricks. If the acceleration of a separated brick is significantly high the trajectory and final landing position of the brick will be influenced by air-drag. The air-drag force is implemented using a user-defined load force in LS-DYNA through a FORTRAN subroutine (*loadud* in *dyn21.f*). The LS-DYNA code is then re-compiled with appropriate object files to create a new executable. The drag force F_d imposed on a brick is given by:

$$F_d = \frac{1}{2} C_d \rho_{air} a v^2 . \qquad \text{(Eq.2)}$$

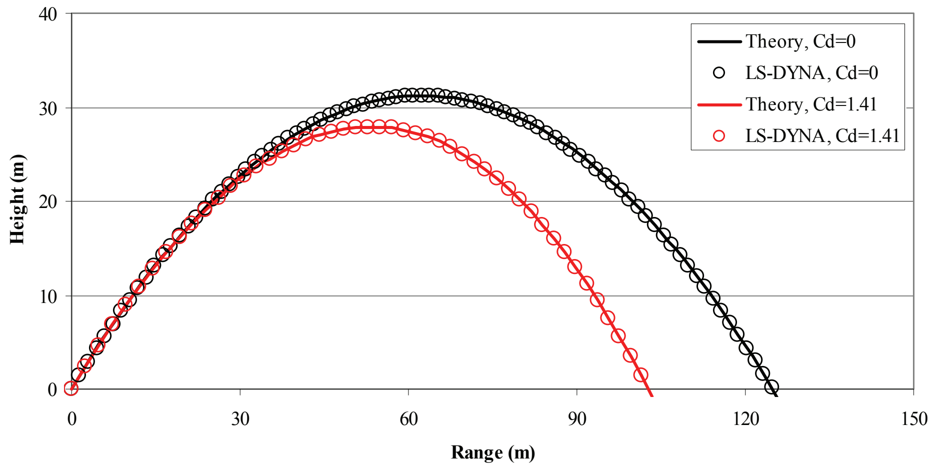


Figure 4: Validation of the air-drag subroutine in LS-DYNA (symbols), result compared to the numerical solution of Eq.2 (solid lines).

Where C_d is the drag coefficient, ρ_{air} is the density of the air, a is the cross-sectional area of the brick and v is the velocity of the brick. As a first approximation the value of C_d and a are assumed to be constant and are based on the properties of a tumbling brick.

The results of the air-drag subroutine are compared with the numerical solution of Eq.2 using Euler's method in Figure 4. The initial conditions assume the brick is launched at an angle of 45° to horizontal. The density of the air was set to 1.2kg/m^3. Simulation results are presented to show the difference between models with air-drag (C_d= 1.41) and without air-drag (C_d= 0). The simulation results presented in Figure 4 compare closely to the numerical solution for each case.

The brick which does not account for air-drag lands approximately 20m further away from the brick which does account for air-drag resistance. This result highlights the importance of accounting for air-drag for bricks thrown over a large distance. The influence of the ground and the effects of brick roll have been ignored in this current analysis.

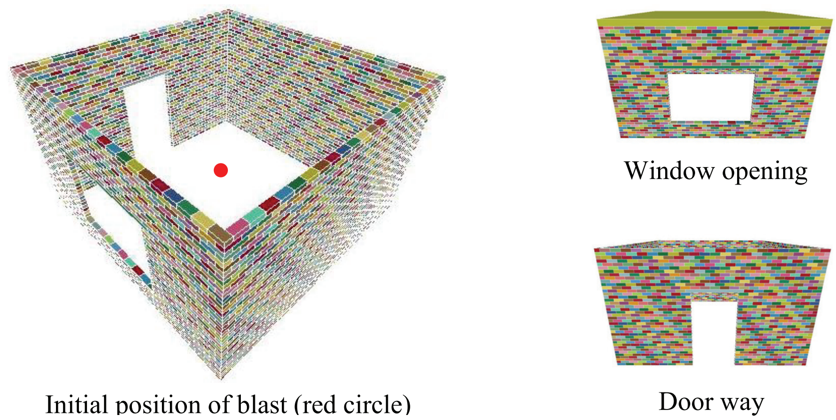


Figure 5 Images showing various views of a simple building structure used to test the implementation of the model.

WALL COLLAPSE AND DEBRIS SCATTER

In this section the collapse and debris scatter of a simplified building structure is simulated, Figure 5. The building consists of four interconnected walls based on a stretcher bond using standard brick dimensions (0.225 x 0.075 x 0.1125m). The model is constructed from approximately 3500 bricks. Two steel lintels are modelled above the window opening and door way. The four walls are pre-loaded with the weight of the roof which is modelled as a rigid structure with the properties of concrete; the roof is simply supported on the four walls and is not constrained. Dynamic relaxation is modelled during the initial stage of the simulation to ensure the walls are under the correct level of pre-stress. The detonation of the explosive is then modelled using the load blast function. A series of images showing the collapse of the building and the debris scatter are shown in Figure 6. The force of the blast is shown to lift the roof above the walls. During this time all four walls collapse outwards forming a cruciform debris scatter shape.

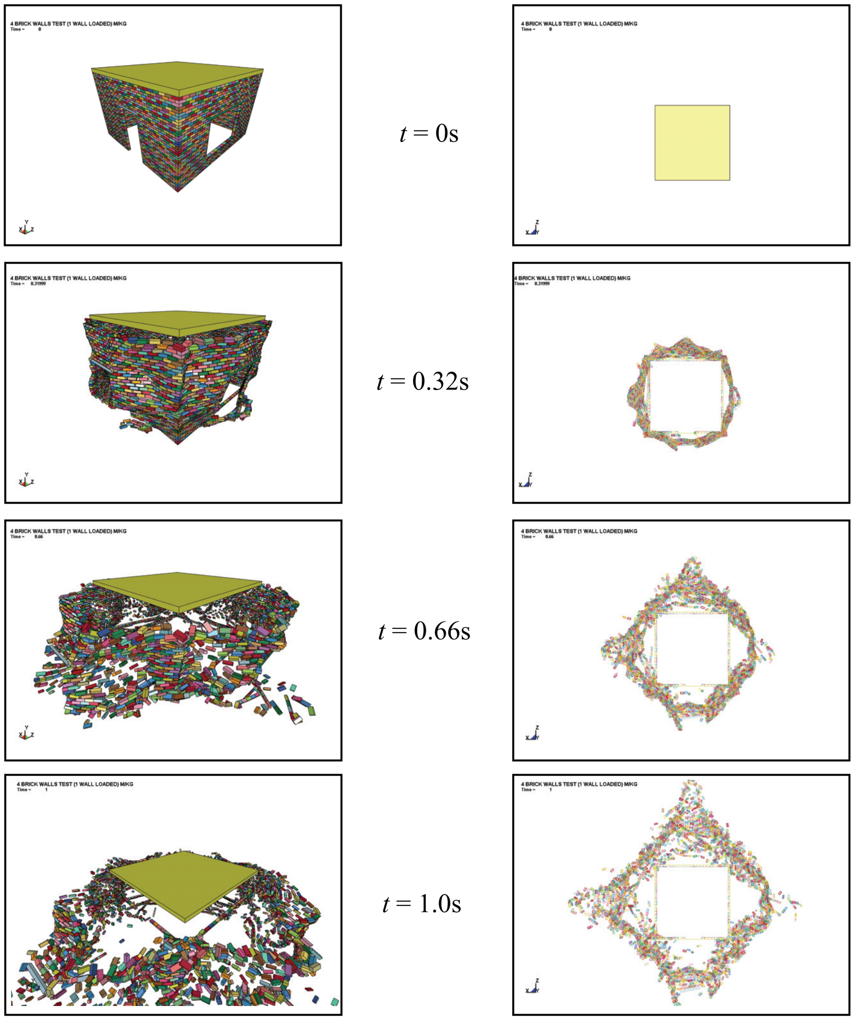


Figure 6 A series of images showing the failure and debris scatter of a building structure

SUMMARY AND CONCLUSIONS

This paper outlines a methodology for the simulation of masonry wall failure and debris scatter. The strength of the brick-mortar bond was modelled using the tiebreak contact within LS-DYNA and validated with comparison to laboratory experiments. A method to simulate the scatter of debris which accounts for air-drag has also been implemented and validated by comparison to theory. The software FE-WALL was written to reduce the significant pre-processing time currently required to generate masonry wall structures using traditional pre-processing software. A particular advantage of the present modelling approach is that masonry wall failure, brick motion and drag are all modelled within a single software package.

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