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Computer prediction of the damage to and collapse of complex masonry structures from explosions

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Abstract

Failure of masonry from blast loads is perhaps one of the most complex events to analyse. The failure mechanisms are complex, but must be accurately represented if the predictions are to be realistic. This paper describes the use of novel computer based methodologies to predict the damage and collapse of masonry structures.

The technique that has been developed uses a combination of an Eulerian finite difference code called GRIM, and a modified version of the DYNA3D finite element code. GRIM was developed by DERA and is used to predict the complex blast loads from an internal explosion in a structure. The modified version of DYNA3D was produced by FNC and used to predict the response of the structure, using the GRIM data as input.

The validation of the technique against trials with a single story building has been reported, in detail, elsewhere. Hence this aspect of the work is covered only briefly in this paper. However, examples to illustrate the accuracy of the technique are included.

The current paper describes the application of the technique to a more complex structure that comprised two stories of masonry walls, reinforced concrete floors and roof and a complex masonry interior structure. Some of the results of the work are presented and they indicate the importance of predicting the trajectory of materials and transfer of load paths subsequent to failure, as both factors can significantly affect the magnitude of the damage to the structure and the injury to any occupants.

1 Introduction

This paper reports work conducted by and on behalf of Defence Evaluation and Research Agency, Fort Halstead (DERA). The work outlined within this paper encompasses two separate studies. The first study involved the development of

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the technique for examining blast damage to masonry structures and the application of the technique to predict the minimum charge size that would cause the collapse of a particular building. This work has been previously reported elsewhere (Reference 1), but it is briefly covered in this paper as it is the basis for the validation of the technique. The second study used the technique to examine the response of a two-storey building, both in terms of the overall damage to the structure and the distribution and injury potential of the debris from the building.

The terminal effects department at DERA Fort Halstead has researched and developed, through Ministry of Defence funding, a sophisticated continuum mechanics based Eulerian Finite Difference code. This code, called GRIM, is capable of simulating multi-dimensional, multi-material (in multi-phase) reacting and non-reacting flows with full rate dependent material plasticity. GRIM was used in these studies to predict the blast load, which was subsequently applied to a DYNA3D model of the building.

The structural damage work was conducted by Frazer-Nash Consultancy Limited (FNC). FNC has been using and extending the capability of the DYNA3D finite element code for over fifteen years. FNC uses versions of the code obtained from the originators of DYNA3D, the Lawrence Livermore National Laboratory in the USA. FNC has been provided with the FORTRAN source code for DYNA3D and is thus able to modify and add to the code to solve complex problems.

2 Development and Validation

The development of the technique for modelling masonry was conducted under tight timescales with the aim of providing a prediction of the response of a particular building to an internal explosion. The prediction was required by DERA prior to undertaking a series of full-scale trials. The ultimate aim of the work was to reduce the number of trials that would be required.

This was the first project in which FNC had examined the response of a masonry structure using DYNA3D. It required the development of a "discrete element" approach to accurately model the structure and some modification of the source code to enable it to cope with large numbers of different materials and sliding interfaces. This work has been previously reported in Reference 1, but is discussed briefly here as it is the basis for the validation of the technique.

2.1 Technique Development

From observation of a blast trial and previous experience it was considered that it was the failure of the mortar, rather than the bricks themselves which is the primary damage mechanism. As such it was considered an acceptable simplification to treat the bricks as rigid bodies. A model was constructed comprising a section of wall with blocks in stretcher bond pattern. Each block in the model was tied to its neighbours on all four sides using a tied with failure contact slideline.

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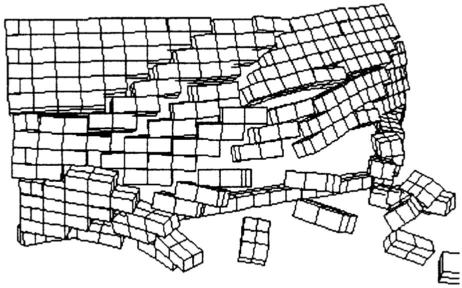

Figure 1: Failure of a Masonry Wall Due to a Blast Load.

These slidelines keep element faces tied together until a prescribed failure criterion is reached. The failure criterion was set to be equivalent to known data on the strength of mortar. After a number of test runs, it was found that each block was required to be composed of a minimum four DYNA3D solid elements (2 x 2 x 1) for the slidelines in the model to remain stable.

The response of a typical wall model to an applied blast loading is shown in Figure 1. The model exhibits the diagonal failure pattern typical of masonry structures and also illustrates how the model fails in an asymmetrical manner, again typical of masonry structures.

2.2 Demolition Predictions

Once developed the technique was extended to the full building structure. The model includes a representation of all outside walls (cavity walls built in stretcher bond pattern), exterior doors and windows and associated lintels. The roof, which was constructed of thick reinforced concrete, was modelled using shell elements that were assigned a linear elastic material model. The complete model was loaded with pressure histories derived from a GRIM model developed by DERA. Reference 1 contains more details of the GRIM work and the excellent validation achieved by comparing the GRIM predictions with measurements in the subsequent trials.

One test had previously been conducted in which the charge size far exceeded that required to cause collapse (2.2kg of PE6). When the DYNA3D model was run with the first pressure loading supplied by DERA it predicted minimal damage to the structure. This prediction was at odds with the observed response of the actual structure. The GRIM model was then re-run with the inclusion of a representation of combustion of explosion products (previously not included) and the DYNA3D model re-run. The new predictions exhibited failure mechanisms, debris throw levels and overall damage similar to those observed in the test.

The DYNA3D model was then rerun with pressure histories representing two lower charge sizes. The results predicted minimal damage for the lowest charge size (0.5 kg of PE6) and that the middle charge size (1kg of PE6) would cause complete demolition of the structure. However, the mechanism of the failure of the structure was very different to that observed in the 2.2kg case. For the 1kg charge size the blast itself does not cause the total collapse of the building, it only induces the collapse of one wall. Most of the building was demolished by the mass and momentum of the roof as it falls onto the remaining structure.

2.3 Validation with Testing

The building was subsequently tested with charge sizes of 0.5, 0.9 and 2.2 kg of PE6. The predictions of the DYNA3D models were shown to be extremely close to the results of the trials in terms of the failure mechanisms, charge size required and debris spread. Figures 2 and 3 show a comparison between DYNA3D predictions and the actual trials results for the two lower charge sizes.

The modelling work significantly reduced the number of buildings that were required to conduct the trials.

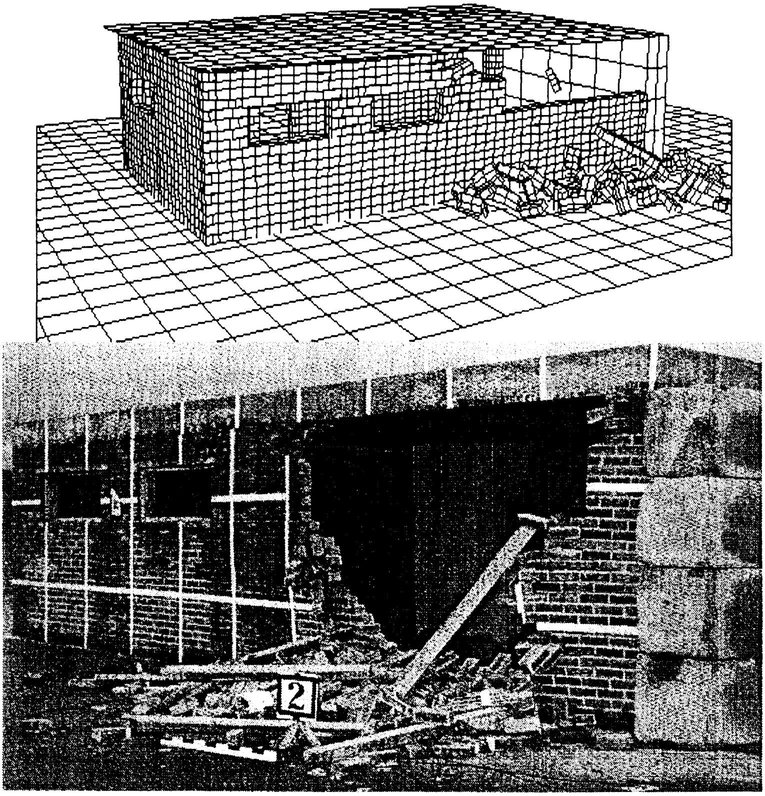

Figure 2: Comparison of DYNA3D Prediction and Trials Results for the 0.5kg Charge Size.

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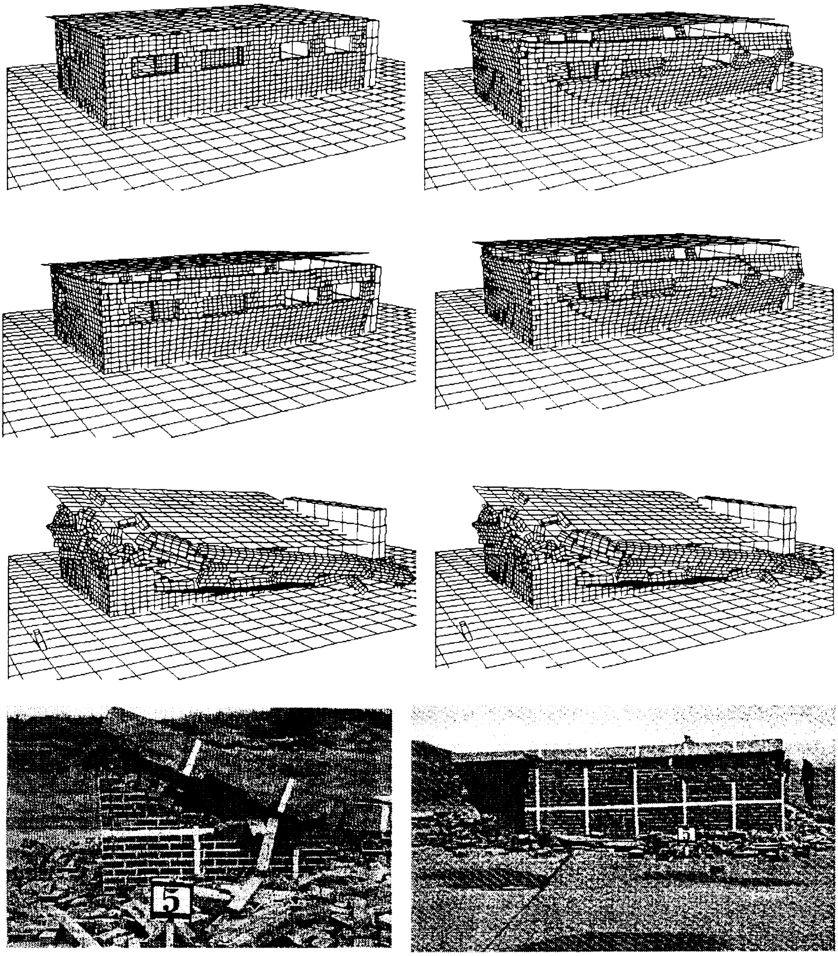

Figure 3: Comparison of DYNA3D Prediction and Trials Results for the 1kg Charge Size.

3 Extension to More Complex Buildings

Recent work using the technique has involved the prediction of damage to a larger more complex building and the prediction of debris trajectories such that the potential for injury to people occupying and nearby to the building can be assessed. The work has involved the construction of a model of a hypothetical two-storey building and assessing its response to three charge sizes in various locations within the building.

The aim of the work was to provide data that traditionally has been obtained using experimental tests. Full-scale tests are extremely expensive and therefore cost can limit the amount of data that is obtained. Furthermore, there are many practical restrictions on the data that can be captured in an experimental trial. For example, it is very difficult to obtain the exact trajectory and speed of every

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brick in a test such that the injury potential of these projectiles can be assessed. The use of computer models to provide this data greatly reduces the costs, timescales and restrictions on the data that can be obtained.

The building that was assessed comprises a two-storey construction with the lower storey partially buried. The building has a complex set of masonry interior walls and reinforced concrete floors and roof. The model of the building included representations of all major building components as follows:

- Exterior cavity walls were represented by a single layer of DYNA3D blocks that had thickness equivalent to two bricks plus the cavity. Each DYNA3D block represented eight actual bricks (two wide by two thick by two high).
- Interior walls were of single brick thickness masonry construction and were represented by DYNA3D elements that represented four actual bricks.
- The roof and ceiling were represented by a layer of DYNA3D solid elements that were assigned a rigid material model. Hand calculations showed that the concrete would not be significantly damaged by the explosions considered. Hence failure in the roof and ceiling was not represented in the model.

As in the previous study, DERA conducted a series of GRIM simulations to generate a blast loading that was subsequently applied to the DYNA3D model. This partially uncoupled approach is based on the assumption that the blast pressure generated by the explosion is not be relieved by the subsequent motion of the walls and ceiling. The GRIM simulations do include some representation of the structural response, but this is at a coarse resolution and certainly not at brick level. This uncoupled assumption has been tested in a number of ways and shown to be largely valid. Clearly the long term venting of the blast pressure from the rooms will not be accurately predicted. However, it is the short-term pressures generated by shock, blast wind and combustion of explosion products that cause the majority of the damage to a building in these events. Such short-term pressures will be reasonably represented in the GRIM models. Indeed, the comparison between test and predictions illustrated by Figures 2 and 3 is clear evidence that this assumption is reasonable

3.1 Results

Approximately twenty runs of the model were conducted during the study and it is therefore only possible to provide a small set of the results in this paper. However, it is possible to illustrate the main findings from the work with the results of two models.

The prediction of damage to the building resulting from an internal explosion of the middle charge size in the upper storey is shown in Figures 4 and 5. Figure 4 shows an external view of the building at several points in time during the explosion and collapse sequence. Approximately half of the building is damaged by the explosion load. The remainder of the building collapses as the weight of

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the roof is transferred onto the remaining structure. The view from above of the internal structure (Figure 5) shows clearly the damage that is caused by the explosion. Furthermore this view shows the trajectory of the debris both internal and external to the building. Detailed analysis of the trajectory of the debris was conducted using a second set of models on individual walls. This data suggests that the potential for injury in the rooms adjacent to the blast is high.

The prediction of damage from a similar explosive placed in the lower floor is shown in Figure 6. It can be seen that the damage to the main structure of the building is not significant. The weight of the upper storey on the lower walls constrains the level of damage that is caused. However, internal damage to the building, and the subsequent injury potential to occupants, was similar to that observed in Figure 5.

The results from these models graphically illustrate the need to fully represent the load paths within a structure if the potential for damage and injury is to be accurately predicted.

4 Conclusions

A technique has been developed for the evaluation of the response of masonry structures to explosions. The technique has been validated against actual trials results and shown to be extremely accurate. The technique is currently being used to evaluate the blast withstand of increasingly complex structures and the injury potential from building debris. The results of the work illustrate the need to accurately represent the failure modes and subsequent shifting structural load paths if the blast withstand, collapse and potential for injury are to be accurately predicted.

Acknowledgements

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References

[1].Dorn, M.R, Nash, M.A. The Numerical Prediction of the Collapse of a Complex Brick Building Due to an Internal Explosion. Structures Under Extreme Loading Conditions - 1997. 1997 ASME Pressure Vessels and Piping Conference. American Society of Mechanical Engineers. Orlando, Florida, 27-31 July 1997.

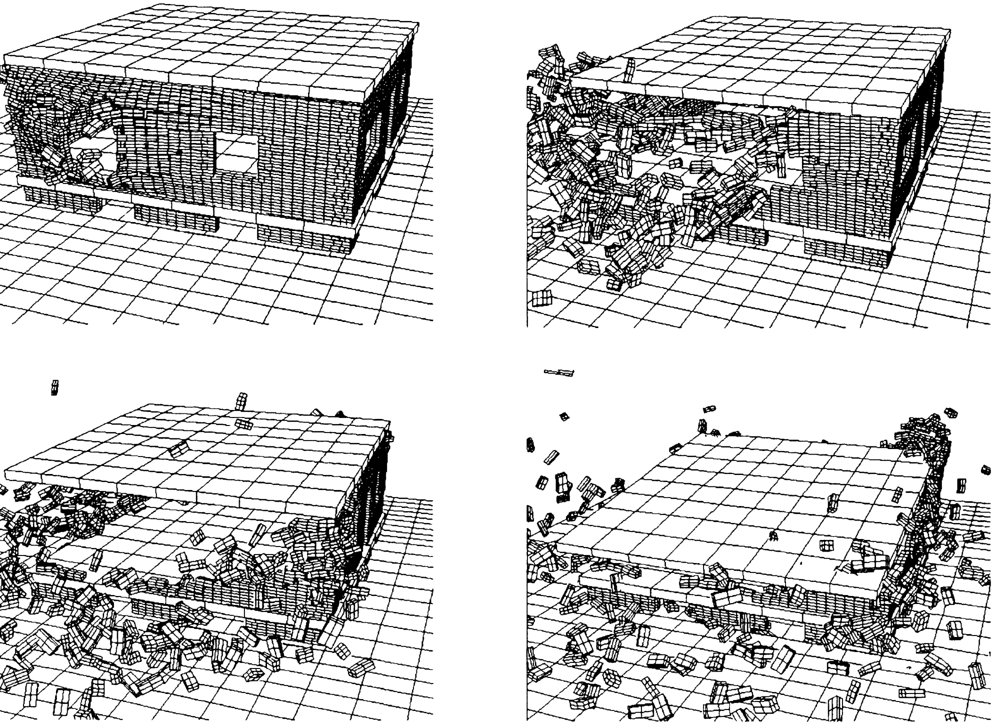

Figure 4: DYNA3D Prediction of Damage to a Two-Storey Building Subjected o an Internal Explosion on the First Floor. Exterior View.

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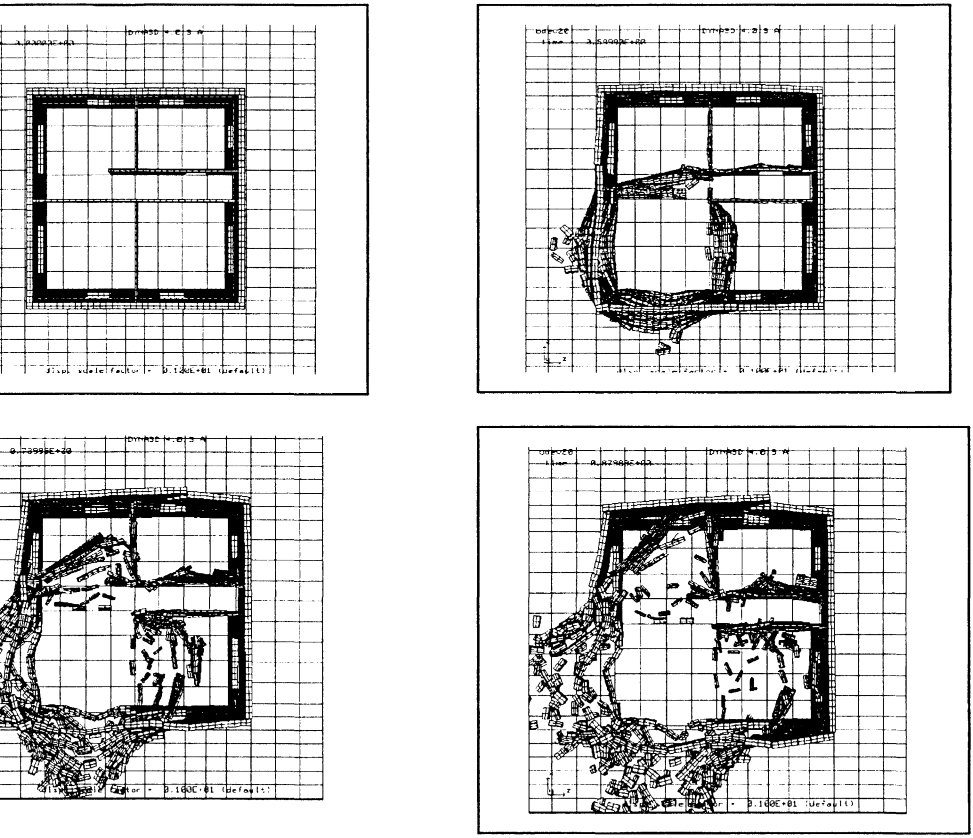

igure 5: DYNA3D Prediction of Damage to a Two-Storey Building Subjected to an Internal Explosion on the First Floor. Internal View.

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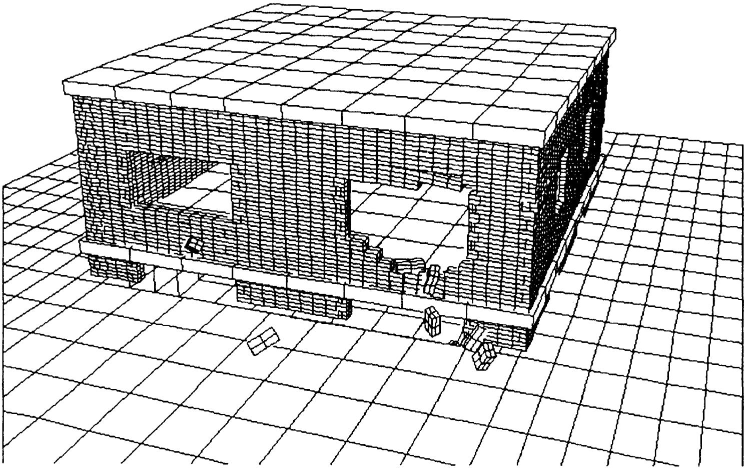

Figure 6: DYNA3D Prediction of Damage to a Two-Storey Building Subjected to an Internal Explosion on the Ground Floor.