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FINITE ELEMENT SIMULATION OF PLATES UNDER NON-UNIFORM BLAST LOADS USING A POINT-LOAD METHOD: BURIED EXPLOSIVES

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Abstract. *There are two primary challenges associated with assessing the adequacy of a protective structure to resist explosive events: firstly the spatial variation of load acting on a target must be predicted to a sufficient level of accuracy; secondly, the response of the target to this load must also be quantified.*

When a high explosive is shallowly buried in soil, the added confinement given by the geotechnical material results in a blast which is predominantly directed vertically. This imparts an extremely high magnitude, spatially non-uniform load on the target structure. A recently commissioned experimental rig designed by the authors has enabled direct measurements of the blast load resulting from buried explosive events. These direct measurements have been processed using an in-house interpolation routine which evaluates the load acting over a regular grid of points. These loads can then be applied as the nodal-point loads in a finite element model. This paper presents results from a series of experiments where a free-flying plate was suspended above a shallow buried explosive. Dynamic and residual deformations are compared with finite element simulations of plates using the experimentally recorded, and interpolated, nodal point-loads. The results show very good agreement and highlight the use of this method for evaluating the efficacy of targets subjected to non-uniform blast loads.

1 INTRODUCTION

The accurate quantification of the loading and structural deformation occurring when a shallow buried charge is detonated has received considerable attention in recent times. The conducted research has equal applicability in both civilian (de-mining) and military (protection from improvised explosive devices) arenas. Being able to design protective structures to withstand these events depends on both the accurate assessment of the loading and an ability to apply these loads in numerical models as a development tool.

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Previous studies have concentrated on assessing the deformation of a target[1-3]. While this is useful for protective system design and platform validation purposes, it fails to directly assess the local magnitude and distribution of loading and hence does not provide sufficient data to accurately validate numerical modelling approaches. Most direct load measurement studies have concentrated on quantifying the impulse imparted to a target, which is typically spatially integrated over the entire target face[2,4-9], and hence in these cases the validation of numerical modelling approaches have a single data point for comparison.

Much attention has also been given to the generation of numerical modelling techniques for the prediction of loading from buried charges. This varies from simplified load curve type models[10] to fully 3D high-fidelity ALE modelling of the explosive, soil and air domains[11,12].

In this paper the authors aim to demonstrate the validity of the point-load method in the prediction of structural deformations. Specifically, numerical modelling has been used to verify that the loading measured in the newly designed experimental test apparatus[13] is accurate i.e. that there is no major source of sensor error. The overall approach to the experimental trial is schematically given in Figure 1, where numerical modelling has been used previously to size elements in the experimental apparatus, and is now used to verify that the loading captured on a rigid target can be used to model the response of a flexible target.

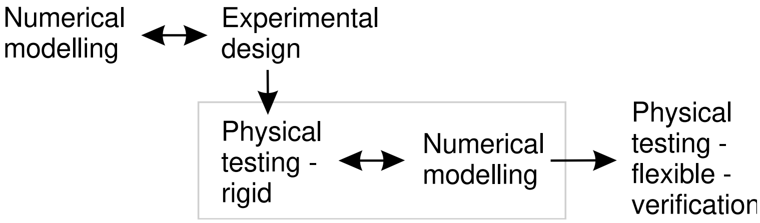

Figure 1: The approach taken to the experimental trials

2 EXPERIMENTAL MEASUREMENT OF BLAST LOADING

The loading regimes experienced by structures subjected to blast loads can broadly be classified into: a) impulse driven (e.g. a rigid free flying mass); or b) deformation driven (e.g. flexible structural targets). In the current work a rigid reaction frame was preferred to allow the Hopkinson pressure bars (which are 10 mm in diameter and 3.25 m long) to be protected. This raises an issue for the use of the measured loads being applied to a deformable target, especially one where the velocity of the deformable target during loading is likely to be high.

To ensure that load curves generated from the rigid measurement face are equally applicable to free-flying deformable targets, point-load curves were interpolated directly from experimental data. These were then applied to a numerical model of the free-flying target with the peak and residual deformations of the plate being directly compared with verification tests of the same arrangement.

The general experimental apparatus is shown in Figure 2a. A single radial array of bars spaced 15 mm apart from 0-150 mm, shown in Figure 2b, was used in the reported analysis. This has since been increased to 4 radial arrays from 0-100 mm giving a total of 17 bars per test. Figure 2c shows the free-flying plate test where an identical configuration was used apart from the rigid plate being replaced by a 500 mm square, 5 mm thick mild steel plate. The peak deformation of the plate was measured using an aluminium honeycomb crush block which was restrained against the rear face of the plate by a timber reaction block and a webbing strap. The residual deformation was measured from the plate directly after it had landed. It was assumed that no further deformation of the plate occurred during landing.

In each test a 78g PE4 charge was used, buried 28 mm below the surface of the soil bed. The soil used was a well-rounded uniform (0.58-1.18 mm) quartz sand known as Leighton Buzzard Sand. The dry density of the soil was 1.6 Mg/m^3 with a gravimetric moisture content of 2.5%. The authors have published much research on the role of geotechnical conditions on the repeatability of buried charge testing[14-16] and as such the reasoning behind the choice of soil type are not elaborated on here. The charge was a standard aspect ratio 3:1 squat cylinder (radius = 28.55 mm) with was detonated from the bottom using a non-electric detonator. No cap was placed on the charge[17]. The stand-off in all tests was 140 mm between the soil surface and the target plate. 10 tests were conducted in total, 5 rigid target pressure measurements (T31-T35) and 5 free-flying plate tests (T36-40).

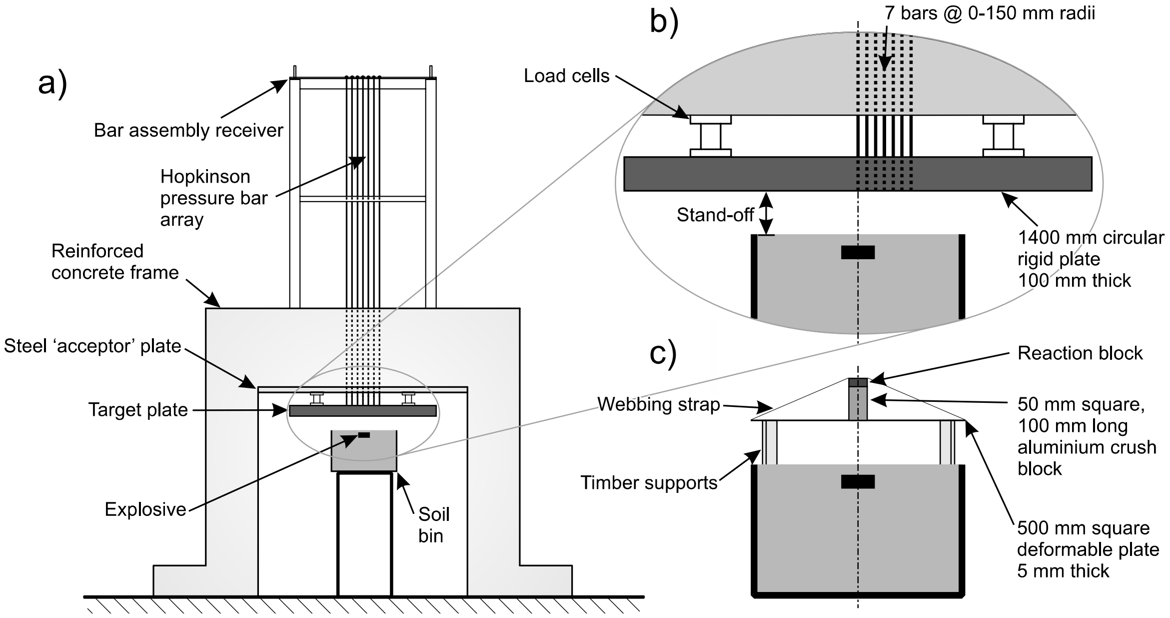

Figure 2: a) The general arrangement of the experimental apparatus b) close in view of the arrangement of the reported testing c) equivalent free-flying deformable plate experiment

3 NUMERICAL ANALYSES

The first stage in developing a set of load curves applicable to the numerical model was choosing an indicative test from the experimental test series. As a single radial array was used in the reported testing it was possible for the asymmetric nature of the ejecta breakout to 'miss' the measurement array, i.e. the geometry of the expanding detonation product/soil bubble was non-coaxial. Examples of coaxial and non-coaxial pressure time histories for the measurement array are shown in Figure 3. Of the 5 repeats done in this configuration T34 was deemed to be the most indicative of the experimental loading. It should be noted that the data in Figure 3 has been filtered using Savitzky-Golay[18] smoothing to eliminate minor electrical noise in the signal.

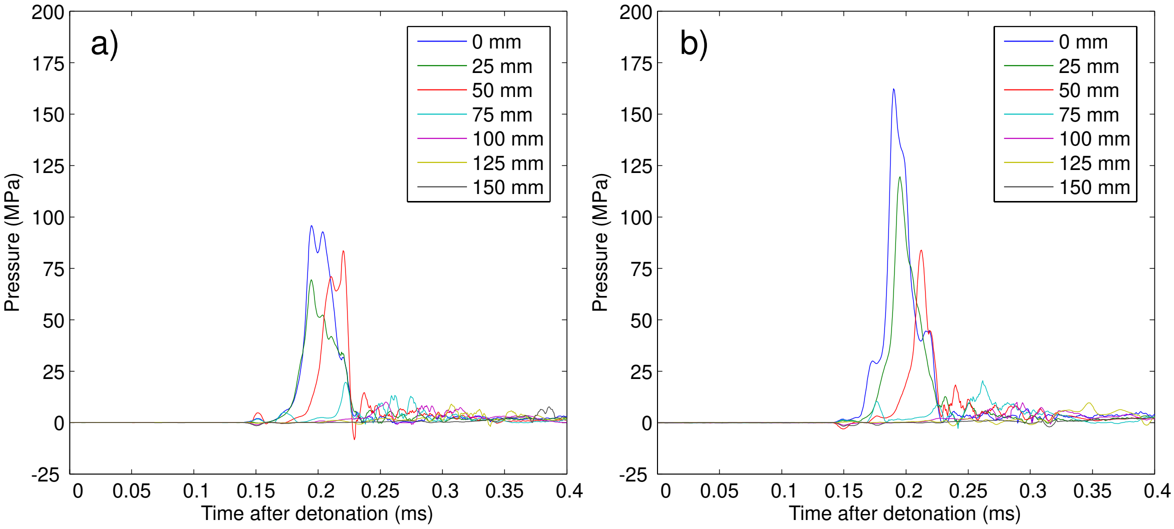

Figure 3: a) T35: example of a non-coaxial breakout, b) T34: example of a coaxial breakout

As the loading was recorded along a single radial array, a methodology by which the load curve at any point on the target plate could be determined was required. The T34 data were initially used to directly interpolate the pressure for any given time step and radial distance so that a series of load curves could be developed. The issue with this approach is that this leads to zones of zero pressure being generated by the direct interpolation when the shock front is between bar locations. This is shown in Figure 4a, whereby the high pressure contours are not continuous. To more accurately model the shock front the interpolation of pressure was done after the individual bar readings had been time-shifted so that the arrival time of the peak pressures in each bar coincided (Figure 4b). The arrival time of the peak pressure was also recorded so that the spatially interpolated data could be time shifted to correctly model the lateral propagation of the shock front across the target face. This method can be also extended where multiple radial measurement arrays are present[13]. This allows a full pressure-time history to be generated for any node based on its radial distance from the plate centre, as shown in Figure 5. As the plate was to be modelled in quarter symmetry the load curves also accounted for superposition at the boundary, again shown in Figure 5.

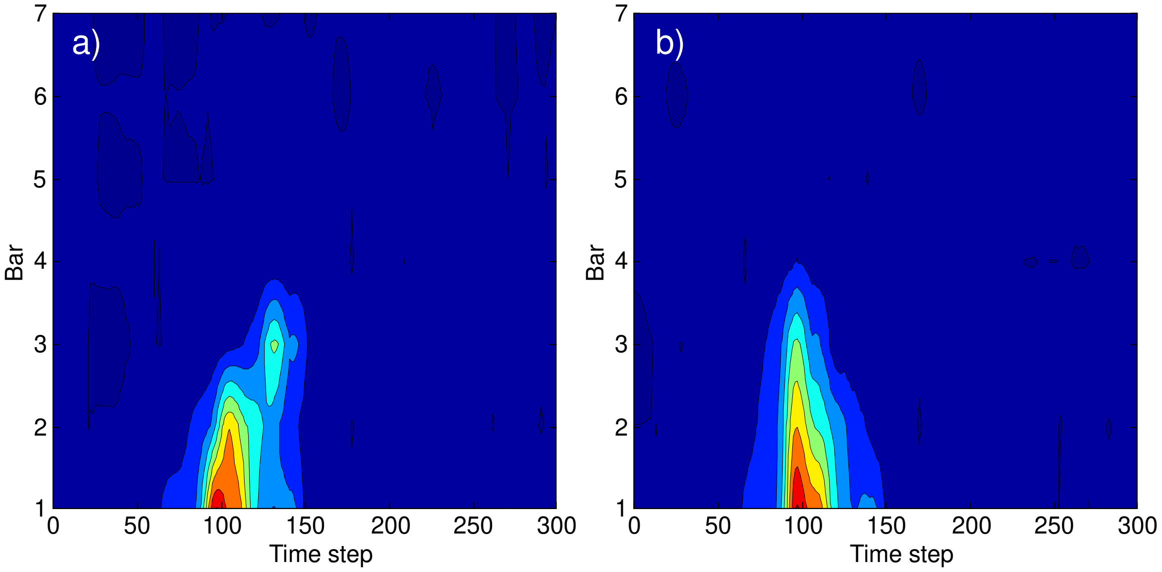

Figure 4: a) Pressure surface for T34 without time shift, b) pressure surface for time-shifted T34 data

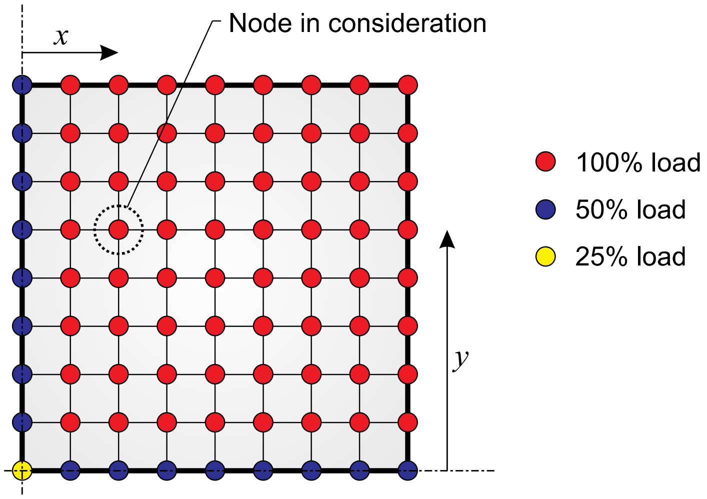

Figure 5: Loading weightings for numerical analyses

4 RESULTS

The modelling was undertaken in LS-DYNA with the steel plate modelled using shell elements and the Simplified Johnson-Cook model (J-C). Initial work was done based on parameters from[19] given in Table 1, this work was later superseded after input from the numerical modelling team at the Defense Science and Technology Laboratory who provided the parameters for mild steel given in Table 2. Both analyses have been retained to assess their accuracy.

RO	E	PR	VP	A	B
7850	210E9	0.3	0	217E6	234E6
N	**C**	**PSFAIL**	**SIGMAX**	**SIGSAT**	**EPSO**
0.643	0.0756	0	0	0	1

Table 1: Initial Simplified Johnson-Cook model parameters[19]

RO	E	PR	VP	A	B
7850	212.7E9	0.3	0	350E6	275E6
N	**C**	**PSFAIL**	**SIGMAX**	**SIGSAT**	**EPSO**
0.36	0.022	0	0	0	1

Table 2: DSTL provided Simplified Johnson-Cook model parameters

The steel plate in the model was 5 x 500 x 500 mm, modelled in quarter symmetry using a 50 x 50 grid, hence the nodal spacing represented 5 mm in real life. The load curves generated from interpolation of the T34 experimental data were applied to each node, and the results of the initial modelling can be seen in Figure 6. The relative displacement was measured between the centre of the plate and the free corner opposite. In the first run the rate effect was removed from the J-C model by setting parameters C and EPS0 equal to zero. An example of the relative plate displacement is given in Figure 7.

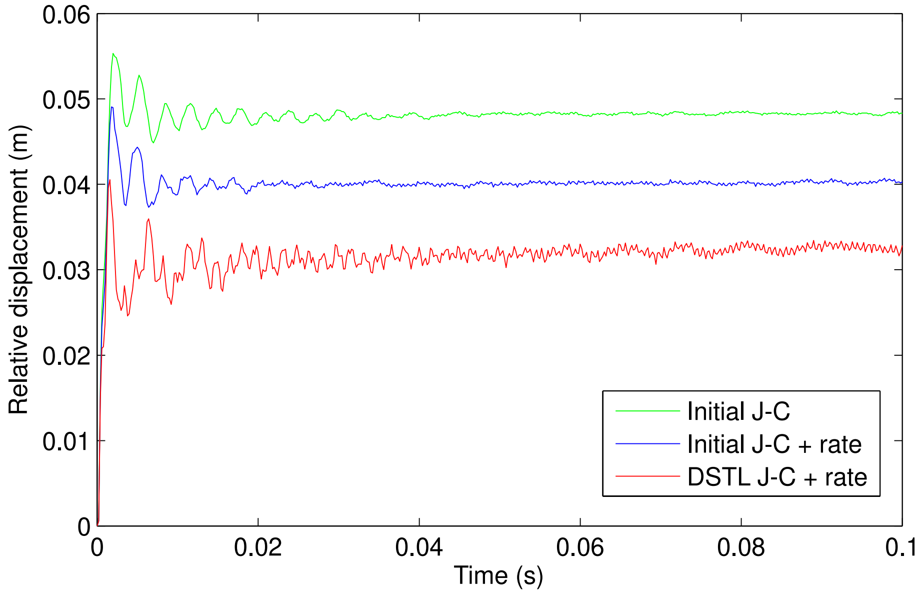

Figure 6: Relative displacement-time plots for the initial analyses

The results from the validation free-flying plate tests are given in Table 3 (where * denotes that the aluminium crush-block was damaged by the falling plate so no measurements could be taken). When compared with the initial analyses it is clear that the DSTL J-C parameters incorporating rate effects are able to give the best estimate of the physical behaviour. These initial analyses were performed blind without access to the deformation data from the physical tests.

Test	Dynamic deflection (mm)	Residual deformation (mm)
36	35	34
37	-*	25
38	34	22
39	37	32
40	35	29
Avg.	35	28

Table 3: Deformation data from the free-flying plate tests (* denotes that the aluminium crush-block was damaged by the falling plate)

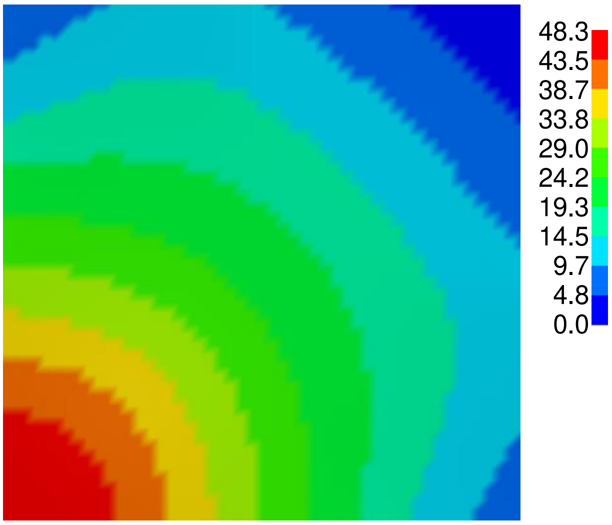

Figure 7: Example output from LS-DYNA showing contours of relative deformation in mm (Residual deformation from the simulation using the initial J-C parameters with no rate effects)

5 DISCUSSION

Given the good correlation between the experimental and numerical data, the authors were satisfied in the fidelity of the measurements made from the physical test data. There remains however, a number of unexplored avenues leading on from the current interpolation / instrumentation scheme. Currently with the 10 mm bars spaced at 25 mm centres there still remains an unquantified region which is open to interpretation. This is shown schematically in Figure 8, the pressure directly above the charge is quantified by both the 0 and 25 mm bars, but outside the charge periphery (r=28.55 mm) between 25 and 50 mm the extent of the region of high pressure is uncertain.

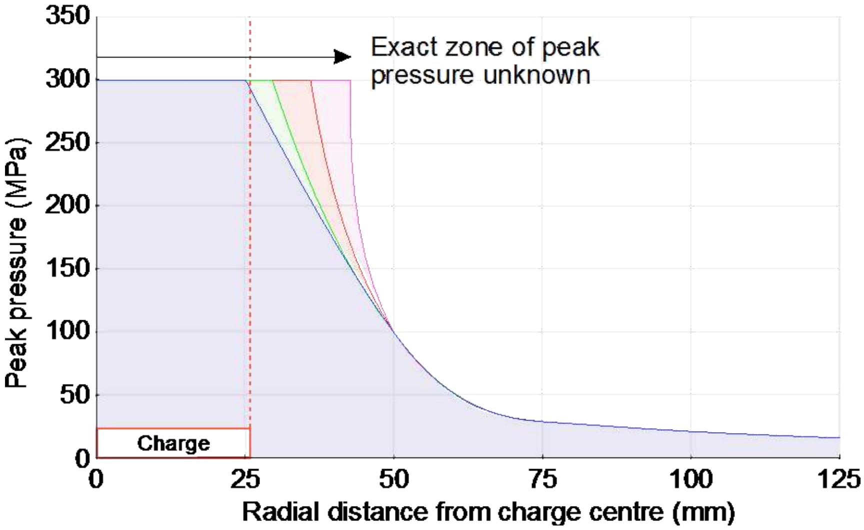

Figure 8: Possible variations in peak pressure

Measuring this experimentally is possible in theory but possibly unwarranted as the problem can be investigated numerically. In all previous modelling the peak pressure (and hence load) has been applied to a single node with a rapid decay of peak pressure occurring with increasing distance from the plate centre. The assumption that the peak pressure only applies to a single node (5 mm x 5 mm) is likely to be questionable. To assess whether the zone of this pressure is critical to the developed load curves (and hence the deflection of a plate), a series of simulations were conducted. In the first of these simulations the central pressure was applied not to a single node, but was instead applied to the entire region between the 0 and 25mm bars (as seen in experimental data in Figure 3a). In a further test this same loading was applied to the zone between 0 and 50 mm. The results, shown in Figure 9, show that increasing the zone of peak pressure reduces the peak deflection in both cases (bringing the predictions inside the spread seen in the experimental data as indicated). In the case of the residual deformation, this has also been reduced, again bringing the numerical modelling in line with physical test data. There appears to be little difference between the two 'smeared' runs with peak deflections being identical, suggesting that the area of the plate directly in line with the charge is most sensitive to the applied blast pressures and accurate quantification of this load is important.

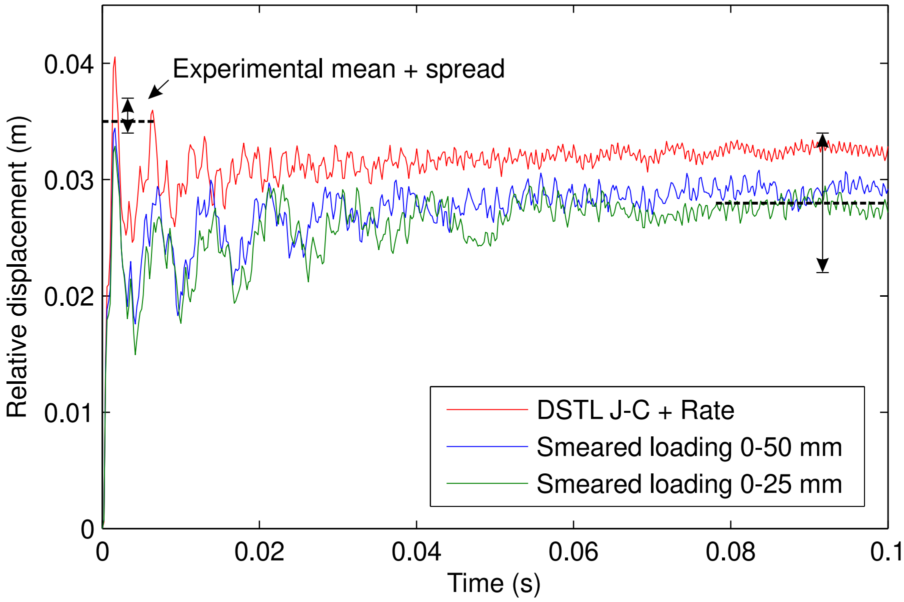

Figure 9: Effect of the smearing of the central loading outside the charge diameter

6 SUMMARY AND CONCLUSIONS

It has been shown that the point load method can be used to accurately load deformable structures based on experimental readings from a fixed plane of reference. Numerical modelling has been used to show that the loads measured from a rigid plate can be used to predict the peak deflection and residual deformations of a free-flying plate.

Attempts were made to improve the agreement by investigating factors that may influence the numerical interpolation of the load curves from the experimental data. This has shown that the plate deformations predicted by the numerical model can be improved by allowing the pressure generated above the charge to be applied evenly over the entire charge diameter increasing the area of influence of the high pressure region.

The current simulations are only valid for a defined stand-off and set of soil conditions. Work is ongoing to be able to generate load curves based on knowledge of the soil conditions and test arrangement without having to interpolate from physical test data.

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