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Near-field blast loading and transient target response: a collaboration between Sheffield and Cape Town

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ABSTRACT: Near-field blast loads are high in magnitude, short in duration, and non-uniformly distributed across the loaded face of a structural element. Experimental characterisation of near-field blast loading and the resulting deformation of a blast loaded target is made difficult by conflicting requirements, namely: robustness to survive the extreme loading conditions; and sensitivity to accurately measure transient behaviour at high sampling frequencies. As such, there is little definitive experimental data in the literature, and the deformation behaviour of plates subjected to non-uniform impulsive loading is yet to be properly quantified. This paper presents an update on the ongoing collaborative research effort between the University of Sheffield, UK, and the University of Cape Town, South Africa. Direct experimental measurements of blast pressure and impulse using an array of Hopkinson pressure bars (Sheffield), and high-fidelity transient plate deformation measurements using digital image correlation (Cape Town) are jointly-used to assess, and develop predictive methods for, the response of blast loaded plates. Simplified predictive methods, based on knowledge of the applied load rather than an assumed distribution, have been developed which show very good correlation with the experiments and physics-based numerical models.

1 INTRODUCTION

The loading generated on the surface of a structure following detonation of a near-field high explosive is extremely high in magnitude, short in duration, and is highly spatially non-uniform. The efficient design of blast protection systems is currently inhibited by an inability to accurately predict these near-field blast loads. There is dearth of well-controlled scientific data in the extreme near-field, which is in part due to the difficulties associated with direct measurement of blast loads and conflicting requirements for experimental techniques: robustness to survive 100s–1,000s MPa pressures and temporal sensitivity to sample pressures at MHz frequencies.

Recent advancements in experimental capability at the University of Sheffield, UK, has enabled the measurement of spatial and temporal distributions of reflected pressures in the region 0.1–1 m/kg$^{1/3}$ (Clarke et al. 2015). The University of Cape Town, South Africa, have developed high-speed digital image correlation apparatus for measuring transient response of targets following a near-field blast (Curry & Langdon 2017). The two institutions began formally collaborating in early 2017 with a view to investigating and developing simplified analysis methods for calculating the response of blast loaded plates. This paper presents an update on the ongoing collaborative research effort (Rigby et al. 2017, Rigby et al. 2019a, Rigby et al. 2019b).

2 EXPERIMENTAL CAPABILITIES

2.1 *University of Sheffield*

Blast load distributions were measured in experiments conducted at the University of Sheffield Blast & Impact Laboratory in Buxton, UK, using the Characterisation of Blast Loading (CoBL) apparatus (Clarke et al. 2015). The CoBL apparatus comprises a pair of reinforced concrete frames with a 100 mm thick, 1400 mm diameter steel target plate underslung and spanning between the soffits of each frame to act as a nominally rigid boundary. 10 mm diameter steel Hopkinson pressure bars are inserted into holes drilled through the thickness of the target plate in a X-shaped arrangement when viewed on plan, and sit flush with the loaded face of the plate. 17 bars are used in total: one bar at the the centre of the target (directly above the centre of the charge) and an additional four bars located at each radial offset of 25, 50, 75 and 100 mm from the plate centre. Axial strain is measured on the perimeter of each bar at 3.125 MHz using strain gauges mounted 250 mm from the loaded face. Strain histories are converted to stress to determine the pressure acting on the bar face and therefore the blast pressure acting at that position on the target.

Figure 1 shows compiled peak specific impulses recorded from six CoBL tests: 100 g PE4 spheres detonated at 55.4 mm clear distance from the explosive surface to the centre of the plate (Figure 1a), and; 78 g PE4 charges, formed into squat cylinders with diameter:height ratio of 3:1, detonated at 168 mm clear distance from the top of the charge to the centre of the plate. The charges were sat in 3 mm thick PVC containers with the cap removed, i.e. the surface of the charge facing the target was not covered by the casing, however additional experimentation (Rigby et al. 2019a) and numerical analysis (Rigby, Fuller, & Tyas 2018) has confirmed that the casing had minimal effect on magnitude and distribution of the loading.

Also shown in Figure 1 is a spline interpolant fitted to the mean values of peak specific impulse at each radial ordinate, for both charge arrangements. Three conditions were applied to the fit: zero gradient at the plate centre; zero gradient and zero impulse at an arbitrary large radial offset from the plate centre; and positive specific for all radial ordinates.

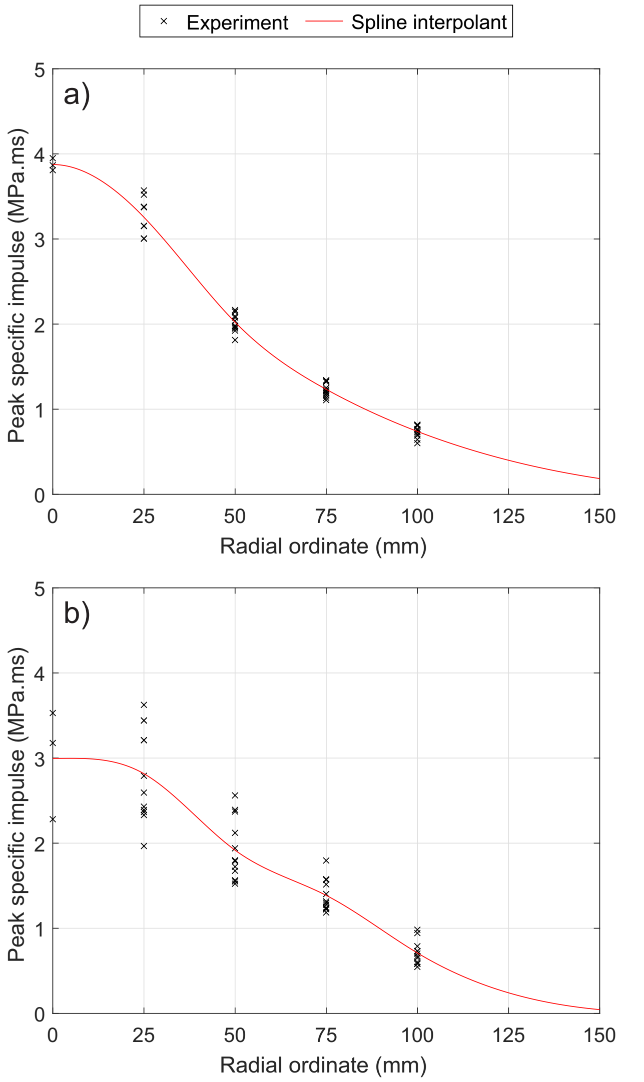

Figure 1: Compiled peak specific impulse at each bar location with fitted spline interpolant: a) Three tests with 100 g PE4 spheres at 55.4 mm clear stand-off; b) Three test with 78 g 3:1 PE4 cylinders at 168.0 mm clear stand-off

2.2 *University of Cape Town*

Digital image correlation was used to measure transient plate deformations at The Blast Impact and Survivability Research Unit (BISRU) at the University of Cape Town, South Africa. The Blast Pendulum at UCT consists of an I-beam suspended from four cables, with a clamping frame at the front to house the test plates and added counterbalance at the rear. The pendulum has recently been adapted to house two IDT vision NR4S3 high speed cameras by removing part of the web and providing a mild steel shroud to protect the cameras and lighting system (Curry & Langdon 2017). The cameras can capture a field-of-view of an area of approximately 300×25 mm at 30,000 fps.

Six DIC tests were conducted and were specified as scaled versions of the UoS tests using Hopkinson-Cranz scaling. For the spherical charge tests, 50 g PE4 spheres were detonated at a clear stand-off distance of 44.0 mm ($55.4\ \text{mm}\times(0.05/0.1)^{1/3}$). For the cylindrical charge tests, 50 g PE4 cylinders were detonated at a clear stand-off distance of 145.0 mm ($168.0\ \text{mm}\times(0.05/0.078)^{1/3}$).

The test plates were made from 400×400×3 mm thick Domex 355MC (7830 kg/m^3) with an exposed circular area of 300 mm diameter when placed in the clamping frame. The plates were fully clamped around the perimeter, with constrained zero in-plane and out-of-plane displacement and constrained rotations at the boundary. Prior to testing, the rear surface of each plate was sprayed with a thin layer of white primer before a random black speckle pattern was added. Figure 2 shows peak out-of-plane deflection-time histories for the spherical charge (a) and cylindrical charge (b) tests respectively.

3 INITIAL VELOCITY UPTAKE

In Rigby et al. (2019a), we detail a method for comparing the imparted impulse directly measured from UoS tests, with the impulse inferred from the UCT tests. Given that an imparted impulse results in an equivalent change in momentum: impulse = mass × velocity, under impulsive loading conditions the specific impulse distribution, $i(x)$, can be inferred from a measured initial velocity distribution, $v(x)$, using the following expression

$$i(x) = v(x)\rho t \qquad (1)$$

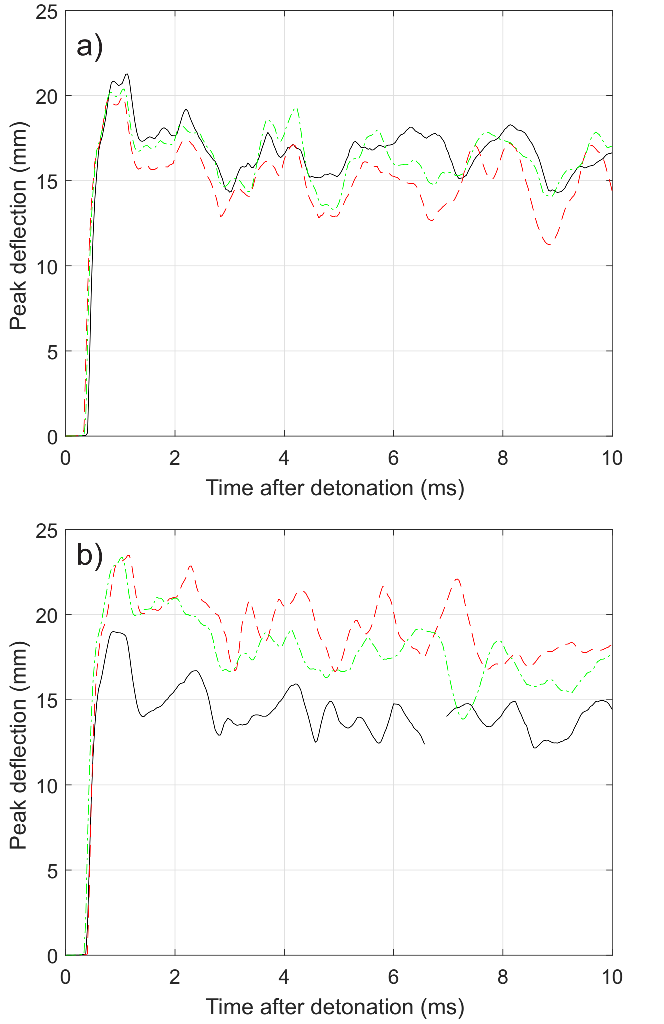

Figure 2: Peak deflection-time histories for tests with: a) spherical charges, and; b) cylindrical charges

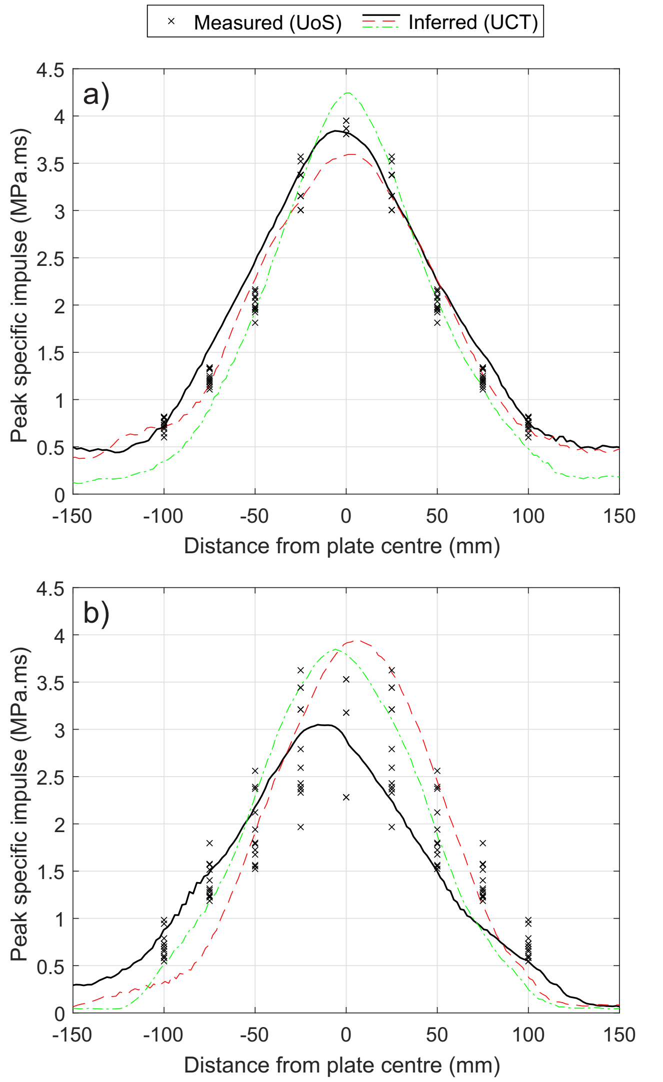

Figure 3: Measured (UoS) and inferred (UCT) specific impulses for: a) spherical, and; b) cylindrical tests, expressed at UoS scale

where x is distance from the centre of the plate, and ρ and t are density and thickness of the plate: 7830 kg/m^3 and 3.00 mm respectively.

Plate velocity profiles, $v(x)$, were determined through temporal linear central differencing of the measured out-of-plane displacement histories at those points on the plate where the DIC software had calculated a displacement history. Peak velocity profiles were taken at the moment the maximum velocity at any point on the plate was reached, and were typically recorded only a few frames after detonation. Peak velocity profiles can therefore be assumed to represent the initial velocity uptake of the plates.

The peak velocity profiles were converted into inferred impulse distributions and scaled up to UoS values using Hopkinson-Cranz scaling to allow the two to be compared, i.e.

$$\frac{x_{UoS}}{x_{UCT}} = \frac{i_{UoS}}{i_{UCT}} = \sqrt[3]{\frac{W_{UoS}}{W_{UCT}}} \tag{2}$$

where W is charge mass, and the subscripts UoS and UCT refer to quantities used in the University of Sheffield and University of Cape Town tests respectively.

Figure 3 shows the inferred specific impulses from the UCT tests expressed at UoS scale using the procedure outlined above, plotted with the specific impulses directly measured from the UoS tests. Here, markers for the UoS test results have been duplicated in both + and − distances from the plate centre for comparative purposes.

The inferred specific impulses closely match the directly-measured values, in particular for the spherical charge tests where little spread is seen. The agreement in the cylindrical charge test data is less good owing to the presence of emergent instabilities in the expanding detonation product cloud (Tyas et al. 2016), however the inferred impulses still follow the same trends and are generally in good agreement with the UoS data.

These results are significant as they suggest that the initial velocity of a blast loaded plate, the initial kinetic energy, and the final displacement profile, are intimately linked to the *distribution* of loading, as well as the magnitude. This also provides the underpinning experimental justification for development of the energy equivalent uniform impulse (Rigby et al. 2019b), described in the following section.

4 ENERGY EQUIVALENT UNIFORM IMPULSE

Previous studies at BISRU, e.g. the experimental work of Nurick & Martin (1989), has shown that there exists a linear relationship between impulse and residual deflection. Whilst this work, and other related research, offers valuable insights into the role of kinetic energy and its influence on plate deformation, to date there have been no studies where the loading distribution is both spatially non-uniform, and *known*, as opposed to an indicative distribution being assumed.

The joint experimental study reported in Rigby et al. (2019a) and summarised in the section above has shown that the initial kinetic energy uptake of a blast loaded plate can be calculated with knowledge of the distribution of specific impulse.

Consider a collection of masses subjected to a distributed impulsive load (Figure 4a). The ability of a discrete mass to share load with its neighbours is dependent on the shear resistance of a series of fictitious lateral spring elements connecting each mass. If these elements possess an *infinite* resistance to shear, then each mass would have the ability to instantaneously transfer load to its neighbours and the entire plate would respond as a rigid body, as in Figure 4(b). Alternatively, if these elements possess *zero* resistance to shear, then the initial velocity profile of the plate would be directly proportional to the impulse distribution, as in Figure 4(c). The kinetic energy of each mass, and therefore the total kinetic energy of the plate, would be dependent on the *distribution of specific impulse acting on the plate*, as was observed in the experimental study in Rigby et al. (2019a).

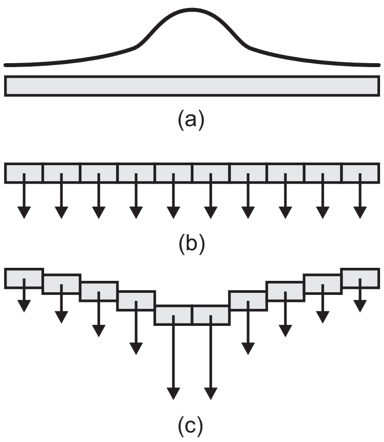

Figure 4: Initial distribution of specific impulse (a), and deformation modes associated with lower bound (b) and upper bound (c) kinetic energy

For situation (b), the kinetic energy of the plate is given only as a function of the total impulse acting on the plate,

$$E_{k,l} = \frac{I^2}{2\rho t A} \tag{3}$$

where I is total impulse, i.e. specific impulse integrated over the area of the plate, A. Since this results in a lower-bound estimate of kinetic energy, this term is given the subscript l.

For situation (c), the kinetic energy is dependent on the distributed specific impulse,

$$E_{k,u} = \frac{1}{2\rho t} \int_A \frac{(i\ \mathrm{d}A)^2}{\mathrm{d}A} \tag{4}$$

Since this results in an upper-bound estimate of the kinetic energy, this term is given the subscript u.

Through manipulation of the above expressions, it is possible to calculate a value of total impulse that, if applied as a uniformly distributed load, would result in the same kinetic energy uptake as the upper-bound kinetic energy associated with the distributed load. This is termed the *energy equivalent uniform impulse*, I_{Ek}, and is given by the following expression:

$$I_{Ek} = \sqrt{\left(\int_A \frac{(i\ \mathrm{d}A)^2}{\mathrm{d}A} \right) A} \tag{5}$$

Hence I_{Ek} can be thought of as the *energy*-averaged impulse, as opposed to the *spatially*-averaged impulse, I.

A detailed parametric study was conducted in Rigby et al. (2019b) which aimed at investigating the relationship between plate deflection and energy equivalent uniform impulse. First, the experimental results from Rigby et al. (2019a) were used to validate a new method for modelling blast loading in LS-DYNA: direct mapping of the experimentally-measured specific impulse distribution (spline interpolant shown in Figure 1a) through assignment of initial velocities for each node on the plate. Results from the validation exercise are shown in Figure 5. There is excellent agreement between the model and experiments and therefore the use of LS-DYNA and the nodal velocity mapping method has been justified for use in the parametric study.

The interpolated impulse distributions for the spherical charges were adapted for the parametric study: Hopkinson-Cranz scaling was used to stretch and shrink both the magnitude and relative radial ordinate of the original curve (Figure 1a) by modelling effective charge masses from 10–200 g. Thus, 'smaller' charge masses would result in a lower magnitude but more centrally-focussed load, and 'larger' charge masses would result in a higher magnitude but more spatially uniform load. For the 10 g charge analyses I_{Ek} was approximately 2.3 times greater than I, whereas for the 200 g charges I_{Ek} was only 1.2 times greater than I. Plate thickness was varied between 0.25–5.00 mm.

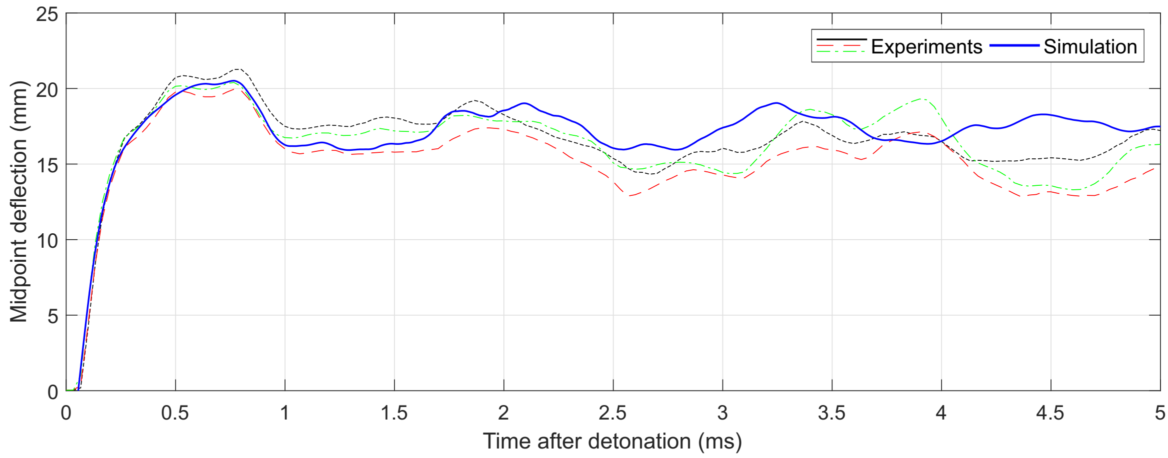

Figure 5: Validation of LS-DYNA against experimental results for 50 g PE4 sphere at 44.0 mm clear stand-off distance

The results of the parametric study are shown in Figure 6. Here, the different markers refer to the two different methods for calculating impulse: I (total impulse) and I_{Ek} (energy equivalent uniform impulse). A linear regression was fit to the relationship between peak deflection and energy equivalent impulse, with an R^2 value of 0.99 indicating a near-perfect fit.

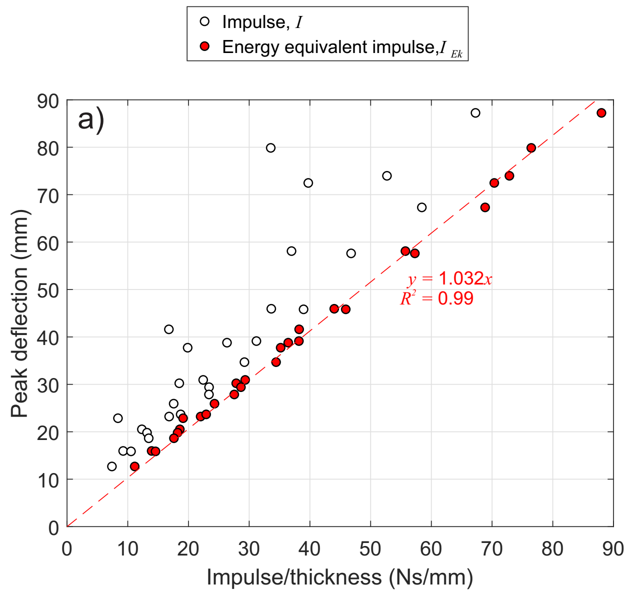

Figure 6: Peak and residual deflection against charge mass for different plate thicknesses

5 SUMMARY AND OUTLOOK

This paper provides an update on an ongoing collaboration between the University of Sheffield, UK, and the University of Cape Town, South Africa. Both institutions have complementary experimental capabilities in the areas of blast load characterisation and dynamic structural response measurements respectively.

To date, a small series of experiments have been conducted at each institution: spheres and cylinders of PE4 detonated at small scaled-distances from instrumented targets, with Hopkinson-Cranz scaling used to express the results at the same scale.

Digital image correlation was used at UCT to measure transient response of circular-spanning, clamped plates, with displacement data used to calculate velocity profiles and determine the initial velocity of the plates, attained shortly after application of the blast load. Conservation of momentum was used to infer specific impulse distribution, which compared well with the directly-measured impulses from UoS tests. Furthermore, the cylindrical charge tests demonstrated higher localised variabilities in specific impulse which was likewise observed as an increased variability in plate deformation and velocity.

These experiments were used to validate LS-DYNA's ability to model plate deformation, and was predominantly used to assess whether the directly-measured impulse distribution could be modelled as a distribution of nodal velocities. This method was confirmed to provide accurate predictions of plate deformation, and was then used to populate a detailed parametric study aimed at investigating the relationship between impulse magnitude, distribution, and peak plate deformation.

A new method for transforming a distributed load into an equivalent uniform load has been presented. The energy equivalent uniform impulse, I_{Ek} has been shown to be strongly positively correlated with peak plate deformation. The energy equivalent impulse method has clear applications for the development of fast-running engineering tools for the prediction of structural response to near-field blast explosions.

This ongoing work shows the benefit of effective research collaboration. The fundamental insights into the link between load distribution and plate deformation, afforded as part of this collaboration, would not have been possible had the institutions been working independently.

6 DATA ACCESS STATEMENT

The data presented in this publication can be obtained on request by contacting sam.rigby@sheffield.ac.uk

7 ACKNOWLEDGEMENTS

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