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Displacement Timer Pins: An Experimental Method for Measuring the Dynamic Deformation of Explosively Loaded Plates

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Abstract

The measurement of dynamic deformation of an explosively loaded plate is an extremely onerous task. Existing techniques such as digital image correlation are expensive and the equipment may be damaged by explosively driven debris/ejecta, particularly if it is necessary to locate such equipment close to loaded elements which are likely to fail. A new, inexpensive and robust measurement technique for use in full-scale blast testing is presented, which involves the placement of displacement timer pins (DTPs) at pre-defined distances from the rear surface of the centre of a plate. A strain gauge on the perimeter of each pin records the time at which the plate comes into contact with the end of each DTP and hence has deformed to that value of displacement, giving a direct measure of the time-varying deformation at a discrete point on the plate. An experimental proof-of-concept was conducted and the results are compared with numerical displacements determined using LS-DYNA. The numerical and experimental results were in very good agreement, which suggests that the proposed experimental method offers a valuable means for determining the full-scale response of structures subjected to blast loads in aggressive environments. Further improvements to the experimental procedure are outlined, along with applications where the DTPs are particularly suited.

Keywords: Blast, Displacement timer pin, Experimental method, Numerical analysis, Plate deformation

1. Introduction

When a blast wave resulting from a high explosive detonation interacts with a structure located close to the explosive, the magnitude of the resulting transient blast load is extremely high and highly spatially non-uniform over the face of the structure [1, 2]. This has the potential to cause significant damage to key building components, and poses a considerable risk to vehicles and civilians, particularly if the explosive is buried within a soil and its effects are focussed vertically by the surrounding soil mass. Accordingly, we must better understand the effects of such loading if we are to design structures to resist these extreme events.

Many past studies have involved experimental investigation into the deformation of plates subjected to blast loads, either in an attempt to better understand shock-structure interaction or to quantify material response to blast loads. In a large number of these studies, the maximum residual plate deformation is measured post-test [3, 4, 5, 6], often in addition to a survey of the final deformed profile of the plate [7, 8, 9, 10, 11]. Whilst this may give a detailed description of the spatial deformation of the plate, it is usually more desirable to determine

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the transient deformation of the target structure, as this is a fundamental requirement for numerical validation of the time-varying features of the loading function. Measurement techniques such as target-mounted accelerometers [12] or laser displacement gauges [13] may be sensitive to shock-related vibration and must be used with care. These methods are primarily used for far-field events where the loading magnitude and hence target displacement is expected to be small, and the risk of damaging expensive equipment is minimised. For more aggressive loading scenarios, there are few techniques available.

Digital image correlation (DIC) has been used to study the full-field dynamic deformation of plates [14, 15, 16, 17, 18, 19]. DIC uses two high-speed video (HSV) cameras filming in stereo to gain a 3-dimensional perspective of the subject of interest. During explosive events, the attack face of a target plate will be optically obscured by flash and afterburn, or ejected debris if the charge is buried, hence the rear face of the target is filmed for DIC. Deformation of the target plate is determined in post-processing using image tracking software. Whilst DIC offers a more complete description of the response of the target structure, it has several limitations. DIC systems are expensive and therefore explosive experiments require heavily engineered structures to protect the equipment; such protection has been achieved in small-scale testing (40 g C4 charge) by embedding the target within a larger reflecting surface [17, 18], but is impractical for medium to large-scale tests. Alternatively the DIC system can simply be moved further from the explosive event, however the distance the DIC system can be moved from the target is limited by the geometry of the test set-up and is a function of the desired target resolution, focal length of the lens, and the distance required between each HSV camera, which increases as distance from the target increases. The risk of potential damage to the DIC system has been somewhat bypassed in ‘laboratory scale’ tests through the use of charge sizes of no more than a few grams of TNT equivalent, which may not be valid when considering conventional explosives buried within soil [1].

There is the need, therefore, to develop an inexpensive and robust measurement technique for use in full-scale blast testing. This paper details the design of displacement timer pins (DTPs): small steel tubes located at pre-defined distances from the rear surface of an explosively loaded plate. A single strain gauge is located on the perimeter of each of the pins, 15 mm from the loading end, which will record a change in strain once the plate comes into contact with the pin. This gives the time at which the plate has deformed to that position. An experimental proof-of-concept test is conducted, where the dynamic deformation of an explosively loaded plate is recorded using five displacement timer pins located 0, 10, 20, 30 and 40 mm in-plane distance from mid-span of a one-way clamped mild steel plate. A numerical analysis is conducted using LS-DYNA [20] to verify the experimental measurements, and comments are made on the accuracy and suitability of the newly proposed experimental approach.

2. Design of the displacement timer pins

When a DTP is impacted, an axial stress pulse will propagate along its length. A strain gauge located some distance from the strike end, orientated parallel to the length of the DTP, will record a finite magnitude and effectively instantaneous change in voltage upon arrival of the stress pulse. For the current application, the magnitude of measured strain is unimportant as the arrival time provides all necessary information. When used in a multiple array, with each DTP set at a unique distance from the rear face of an explosively loaded target, a detailed displacement-time history of the deforming plate can be drawn, with each DTP giving the time at which the plate has deformed to a certain value within the chosen measurement range.

The DTPs were constructed from 6 mm diameter, 300 mm long stainless steel tubes with a 1 mm wall thickness, each weighing ~30 grams. A Kyowa KFG-5-120-C1-11 foil strain gauge was attached to the perimeter of the steel tube using CC-33-A cyanoacrylate gauge cement, 15 mm from the strike end of the DTP. The signal wires were soldered to the strain gauge terminals on the exterior of the tube and were routed through the tube via a 4 mm long notch cut into the surface, perpendicular to the length of the pin. This prevented damage to the cables during use and allowed free movement of the DTP before being fixed in place, allowing it to be easily loaded in position.

Each pin was seated in a 12 mm diameter, 50 mm deep PTFE bushing, allowing some movement of the timer pin post-impact. Electrical insulating tape held the DTP in place once the distance from the target was set, the aim of which was to gradually arrest the DTP post-impact rather than risking the wiring being stripped when coming into contact with the support. Six bushings were press-fitted into a 50 mm thick steel disk which was housed within a steel ring welded to a 50×50×5 mm square hollow section (SHS). The SHS was attached to the test frame, 250 mm from the far rear face of the target. One central pin and a radial arrangement of up five additional DTPs can be accommodated at a radius of 18 mm from the central pin at 72 degree intervals. The location for the housing was selected such that the shock transmitted through the test frame would arrive after the pins had recorded an impact with the plate. A schematic of the DTP array is shown in Figure 1.

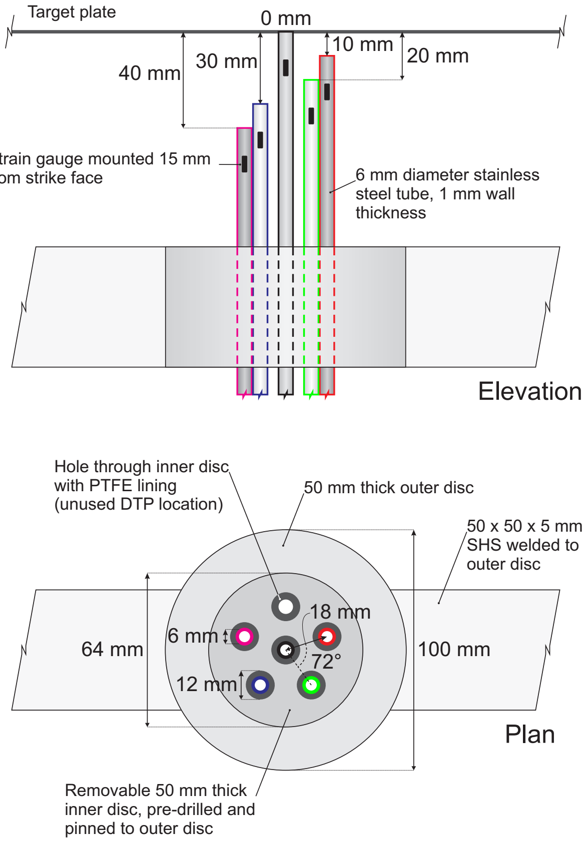

Figure 1: Schematic of the DTP housing and DTP array used in this study

The reader should be made aware that the following assumptions have been made with regards to the DTPs. Firstly the difference in deformation at the plate centre and the non-central pins (located 18 mm lateral distance from the plate centre) was assumed to be negligible. This is confirmed through the numerical results in Section 5.1. Secondly, the DTPs were assumed to offer little resistance to the deforming target, which is justified by low friction of the PTFE bushing and a mass that is several orders of magnitude lower than the deforming plate, hence negligible momentum transfer. Finally, the time delay between the plate impacting the DTP and the strain gauge recording a change in voltage was assumed to be insignificant relative to the time taken for the plate to deform. This is justified by considering a stress pulse travelling at an approximate elastic wave speed of 5000 m/s. This pulse will reach the gauge location 3 μs after impact (note: if the magnitude of impact stress is sufficient to cause plasticity in the DTP, an elastic stress component will still travel at the elastic wave speed and be recorded at the strain gauge after this time). The deformation of the plate is expected to last in the order of a few milliseconds, hence this difference is negligible.

3. Experimental proof-of-concept

An experimental proof-of-concept test was performed to verify the DTPs as a viable method for measuring the dynamic deformation of an explosively loaded plate, with photographs of the test arrangement shown in Figure 2. A 200 g PE4 charge was press-formed in a spherical mould and supported 125 mm above the centre of a 4 mm thick steel plate. The charge was situated on a 50 mm thick, 100×300 mm polystyrene beam, which spanned onto two machined blocks of polystyrene and was secured firmly with duct tape (Figure 2(c)). Machining of the charge support enabled the stand-off to be accurately controlled, and the frangible polystyrene structure could be assumed to have no influence on the development and propagation of the blast wave. The position of the charge support and the plate centre was measured using a steel rule and was marked on the loaded face of the target plate prior to the plate being fixed into the test frame. The centre of the charge support was measured on a mill bed digital read-out and was marked with a fine line marker pen prior to being placed on the target. This ensured the charge was located centrally above the plate. After the charge was positioned, the stand-off (from charge centre to target plate) was measured and confirmed to be within ±1 mm tolerance. A medium intensity DaveyDet electrical detonator, with a net explosive quantity (NEQ) of 0.8 g PETN, was inserted into the centre of the charge from above, giving an effectively spherically symmetric point detonation. A breakwire was wound around the circumference of the detonator at a distance of one charge radius from the detonator end, such that it sat flush with the surface of the charge once the detonator was embedded. This enabled accurate quantification of the time of initiation to provide a triggering signal.

The 4 mm thick steel plate was situated within a large, effectively rigid clamping frame (Figure 2(a)). The boundary conditions were specified such that the plate had clear dimensions of 640×630 mm, and was one-way spanning, clamped in the 640 mm span with the edges of the 630 mm span free to displace in-plane, with 5 mm clear either side to prevent the plate from striking the clamping frame whilst displacing. The clamping frame sat on four 50×50×5 mm SHSs bearing onto a flat, level, reinforced concrete ground slab. There was a clear distance of >4 m from the frame to any nearby objects, ensuring no reflections from the blast wave would arrive during the displacement phase of the target plate. The DTP housing was located directly below the centre of the plate (Figure 2(b)). The central pin was situated flush with the back face of the target, with four subsequent pins at 10, 20, 30 and 40 mm clear distance from the plate (Figure 1). This distance was measured twice using a magnetic steel rule; once before the pins were held in place and once afterwards to ensure a tolerance of ±0.5 mm was met. Preliminary numerical modelling indicated that the plate would not deform by more than 50 mm, hence the sixth DTP hole was left unused. Information of the target response, however, is not required *a priori* and can be determined from preliminary testing using various DTP arrangements.

Strain data was recorded using a TiePie Handyscope 4 digital oscilloscope, recording samples at 1.56 MHz and 14-bit resolution. The oscilloscope was triggered to record following a change in voltage of the breakwire signal, with a 10% pre-trigger allocated. 20,000 samples were recorded in total, giving an effective post-detonation recording time of 11.5 ms. The plate was expected to impact the final DTP within this time with a suitable margin for any potential triggering error. The reader should be aware of the conflicting requirements of long recording time

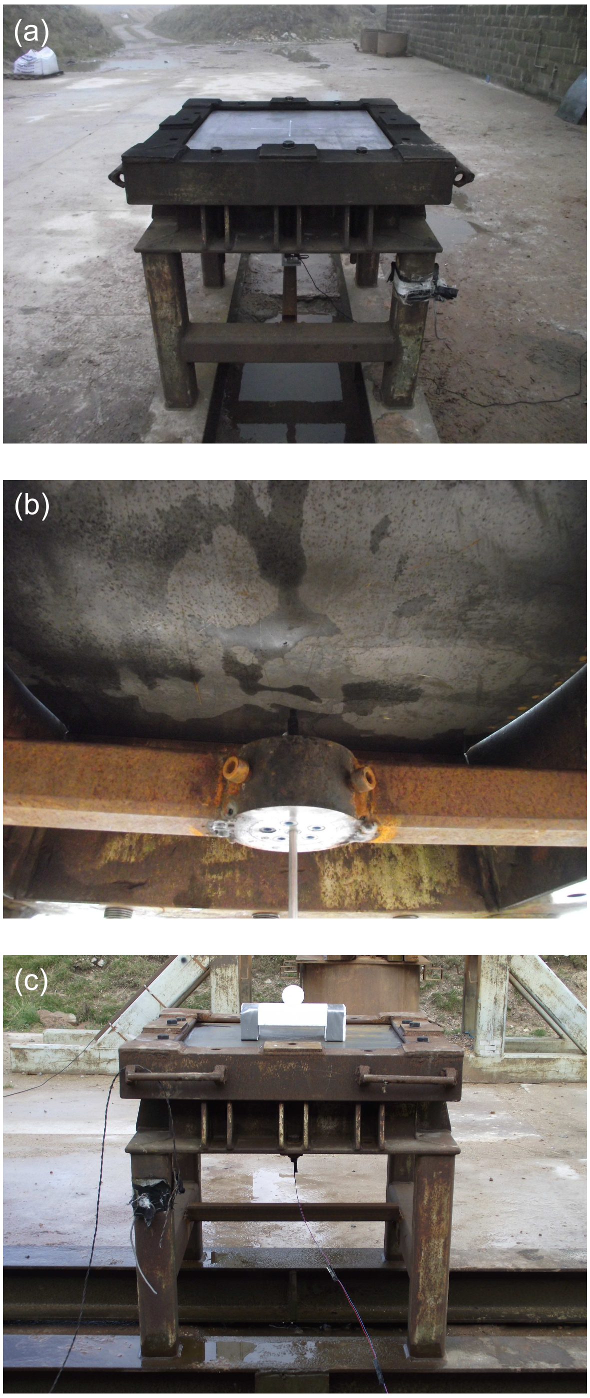

Figure 2: Photographs of test arrangement; (a) test frame, (b) close-up of displacement timer pin (note: only central pin has been loaded), (c) Fully instrumented test setup with charge in place

(in order to capture all features of the deformation history) and high sampling frequency (for accurate recordings of DTP impact times). The selected values were seen as a suitable compromise for the current test arrangement.

Figure 3 shows the experimentally recorded voltage-time histories, which have been zeroed vertically by subtracting the pre-trigger mean voltage of each channel. All traces exhibit a clear rise in voltage upon impact of the plate with the DTP. From knowledge of each DTP location, the voltage-time histories have been converted into a displacement-time history at the centre of the plate. Impact times of each DTP are also shown. A signal spike at $t = 0$ can be seen in all traces, which is a result of cross-talk from the breakwire signal. This noise has a very short duration and does not subsequently influence the recordings from the DTP channels, however care must be taken to eliminate this data during post-processing if using an automatic code to detect a rise in voltage associated with impact of the plate with the DTP for each signal channel.

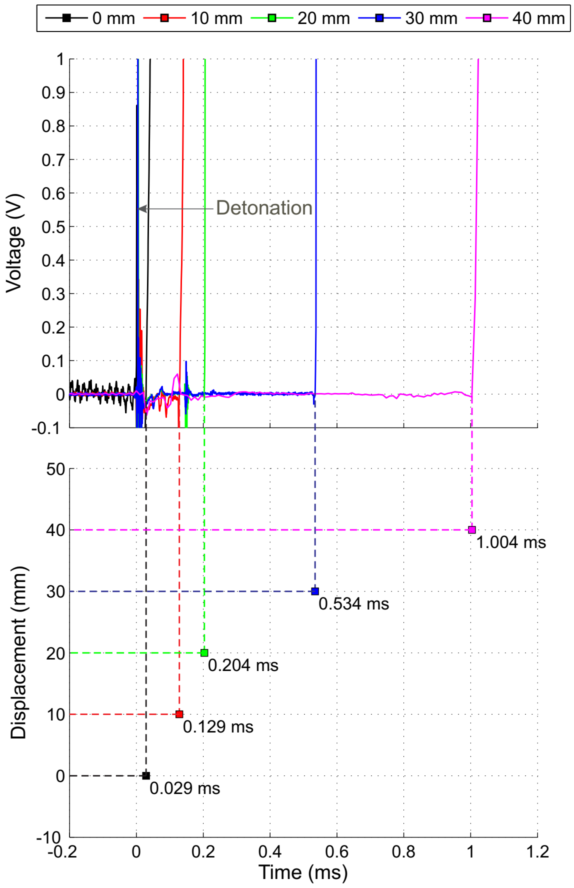

Figure 3: Raw experimental voltage-time traces (with mean pre-trigger voltage subtracted from each channel) and inferred displacement-time history at plate centre

4. Numerical analysis

4.1. Introduction

The LS-DYNA explicit finite element code [20] was used to simulate the experimental trial. In this article, numerical modelling serves as verification of the proposed experimental measurement technique. For this reason, a detailed account of the model setup is provided in order to give the reader confidence in the methodology and results used for verification. The plate was modelled using Lagrangian shell elements situated within a Multi-Material Arbitrary Lagrangian Eulerian (MM-ALE) air domain. The explosive and air were treated as separate parts, allowing the detonation process and blast wave propagation to be modelled using the multi-material solver, with the Van Leer advection method with half-index shift [21] specified as it is generally recommended for high explosive problems.

4.2. Model setup

4.2.1. Air and explosive

The air was modelled using the EOS_LINEAR_POLYNOMIAL equation of state (EOS)

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \tag{1}$$

where $C_0, C_1, C_2, C_3, C_4, C_5, C_6$ are constants, $\mu = \rho/\rho_0 - 1$, ρ and ρ_0 are the current and initial densities of air, and E is the specific internal energy. If the variables C_0, C_1, C_2, C_3 and C_6 are all set to equal 0, and C_4 and C_5 are set to equal $\gamma - 1$, where γ is the ratio of specific heats ($\gamma = 1.4$ for air), the equation reduces to the ideal gas equation of state

$$p = (\gamma - 1)E\rho/\rho_0 \tag{2}$$

The air was modelled using the MAT_NULL material model, with material model and EOS parameters shown in Table 1. An initial specific internal energy, $E_0 = 253.4$ kPa, was given to set the atmospheric pressure to 101.36 kPa.

The explosive was modelled with MAT_HIGH_EXPLOSIVE_BURN material model and Jones-Wilkins-Lee (JWL) semi-empirical equation of state, EOS_JWL [22]. The density, ρ, detonation velocity, D, and Chapman-Jouguet pressure, P_{CJ}, of the explosive are defined in the material model and control the programmed detonation of the explosive. The pressure, volume, energy relation of the explosive products post-detonation is given as

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \tag{3}$$

where A, B, R_1, R_2 and ω are constants, V is the volume and E is the specific internal energy as before. The parameters for PE4 are also shown in Table 1, where the initial internal energy for PE4, E_0, is specified. PE4 is nominally identical to C4, hence the parameters used in this study were taken from the values for C4 published by Dobratz & Crawford [23].

The airblast analysis was initiated using 2D axi-symmetric MM-ALE elements in a graded radially symmetric mesh. The explosive and air were meshed as separate entities, with contact between the two parts achieved with shared nodes along the boundary. The polystyrene charge support was considered negligible and the problem was assumed to be an idealised free-air detonation with the NEQ of the detonator neglected and a point source detonation assumed using *INITIAL_DETONATION. Interaction of the blast with the steel plate was not considered in this stage of the analysis, hence only the parts corresponding to the air and explosive were included. The 2D analysis was terminated when the shock front had propagated 120 mm: 5 mm short of the target plate to account for numerical rounding of the shock front. This information was then mapped onto a 3D domain – which included parts corresponding to the plate – at $t = 21$ μs using *INITIAL_ALE_MAPPING [24]. This remapping technique has been shown to greatly reduce computational errors associated with high pressure gradients and cross-element mass movement in the early stages of detonation/expansion [25]. Quarter-symmetry was utilised for the 3D analysis, with a domain of 0.315 × 0.3 × 0.32 m specified, with the z direction relating to the clamped span of the plate, the x direction relating to the unsupported span of the plate, and the y direction relating to the direction of in-plane displacement of the plate. Rigid boundary conditions were specified for the symmetry planes ($x = 0$ and $z = 0$ planes) and free boundary conditions were specified elsewhere.

Air	MAT_NULL							
	ρ_0 (kg/m^3)							
	1.225							
	EOS_LINEAR_POLYNOMIAL							
	C_0 (Pa)	C_1 (Pa)	C_2 (Pa)	C_3 (Pa)	C_4 (-)	C_5 (-)	C_6 (-)	E_0 (Pa)
	0.0	0.0	0.0	0.0	0.4	0.4	0.0	253.4E3
PE4	MAT_HIGH_EXPLOSIVE_BURN							
	ρ_0 (kg/m^3)	D (m/s)	PCJ (Pa)					
	1601	8193	28.0E9					
	EOS_JWL							
	A (Pa)	B (Pa)	R_1 (-)	R_2 (-)	ω (-)	E_0 (Pa)		
	609.77E9	12.95E9	4.50	1.40	0.25	9.0E9		
Steel	MAT_SIMPLIFIED_JOHNSON_COOK							
	ρ_0 (kg/m^3)	E (Pa)	ν (-)	A (Pa)	B (Pa)	n (-)	C (-)	
	7850	212.7E9	0.3	350E6	275E6	0.36	0.022	

Table 1: Material model and equation of state parameters for air, PE4 [23] and steel [26] used in this study

4.2.2. Steel plate

The plate was discretised into a grid of 100 × 100 Belytschko-Tsay shell elements with four integration points through the thickness of the shell, again using quarter-symmetry. The plate was modelled using the simplified Johnson-Cook material which relates the equivalent stress, σ_{eq} to the equivalent strain, ϵ_{eq}, and equivalent strain rate $\dot{\epsilon}_{eq}$ [27],

$$\sigma_{eq} = \left(A + B\epsilon_{eq}{}^{n}\right)\left(1 + C\ln\frac{\dot{\epsilon}_{eq}}{\dot{\epsilon}_0}\right) \tag{4}$$

where A, B, n and C are material constants and $\dot{\epsilon}_0$ is the reference strain rate of 1 s^{-1}. Thermal softening effects and damage are ignored in the simplified Johnson-Cook material model. No failure criterion was included as the plate was not loaded to failure in the experiment. The Johnson-Cook parameters used for steel in this study are given by Clarke et al. [26] and are also shown in Table 1 along with the density, ρ, elastic modulus, E, and Poisson's ratio, ν, used for the plate.

Fluid-structure coupling was achieved using the *CONSTRAINED_LAGRANGE_IN_SOLID keyword with the penalty contact specified as 'normal only, compression and tension'. This is as an alternative to applying semi-empirical predictions directly to the plate [13, 28]. The plate spanned 0.64 m in the z direction (0.32 m in quarter symmetry), was unsupported in the 0.63 m x span (0.315 m in quarter symmetry), and was free to displace in the y direction. Boundary conditions and symmetry axes were achieved using nodal point constraints, with all displacements and rotations constrained along the clamped edge of the plate ($z = 0.32$) and appropriate displacements and rotations constrained along the symmetry axes.

5. Results and discussion

5.1. Results

Figure 4 shows the numerical displacement-time history of the node situated at the centre of the plate, along with the experimental displacement-time history determined from DTP impact times (as in Figure 3). The numerical results show excellent correlation with the experimental recordings, with the 0, 10 and 30 mm DTP impact times effectively coincident with the numerical displacement-time curve. The numerical results have therefore adequately proved the concept of using a DTP array for the measurement of transient deformation at a significant point on an explosively loaded target. Whilst it is accepted that further testing is required to explore the full remits of this technique, it is sufficient to say at this stage that the DTP method has been shown to offer a valuable new experimental approach.

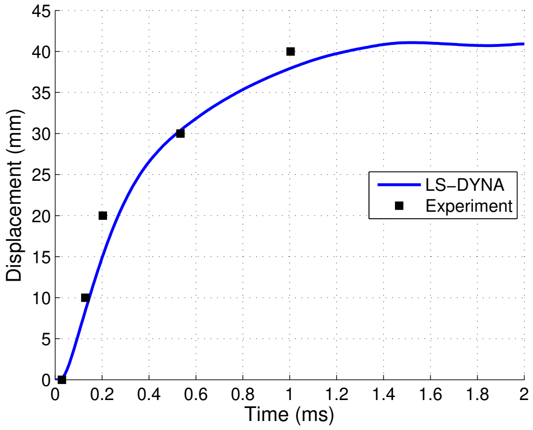

Figure 4: Numerical and experimental displacement-time histories (experimental error bars are negligible at this scale)

Further, the results from the numerical analysis show that measuring the displacement of the plate at 18 mm lateral offset from the centre (as was the case with the radial pins in the experimental work) would result in a peak deflection of 0.3 mm less than at mid-span. This is within the ±0.5 mm tolerance when situating the DTPs 10–40 mm from the target rear face, and confirms the assumption that radial DTPs can be used to measure target deformation at discrete points without any significant source of error from the DTP placement. Care should be taken, however, when performing small-scale testing using a DTP array, as this measurement difference coupled with an increased DTP mass relative to the plate mass may influence the validity of results.

5.2. Critique of the DTP method and improvements

The DTPs have several key advantages. Firstly, the pins can be manufactured in-house with off-the-shelf components and provide critical data from environments that may otherwise prohibit the use of expensive equipment.

Whilst the DTPs can be re-used, the comparatively low cost of each sensor suggests that its application is particularly suited to environments where other measurement apparatus may be critically damaged. Secondly, data generated from the voltage-time signals can be processed with commonly available software such as Microsoft Excel or MatLab and does not require specialist training.

The experimental proof-of-concept presented in this article was chosen specifically for a case where existing numerical modelling approaches can offer suitable verification [2]. In concept, however, the DTP approach is not limited by this requirement and can be used for measuring deflection of complex target geometries and materials, confined or internal explosions, and vehicle undersides subjected to shallow buried explosives. For these situations, DIC/HSV or laser displacement gauges may be unsuitable due to either insufficient field-of-view, the proximity to loaded elements, or the likelihood of damage to expensive/irreplaceable equipment.

By using extra DTPs within the central array, or by locating additional arrays at other points of interest on the target (e.g. quarter-span), the experimentalist can attain high-fidelity displacement measurements for use in either parametric study or model validation. This comes with the caveat that each separate DTP will require a separate channel for data capture. Each test facility will therefore have a limit on the amount of DTPs they can employ, however this is a limit imposed by the availability of hardware, rather than of the experimental equipment itself. Recent experimental work by the current authors utilises up to 20 channels of data capture [1].

Furthermore, locating several DTPs at the same in-plane and radial distances from the plate centre will give an indication of the temporal variance in spatial distribution of plate deformation. For example, non-uniform breakout of the soil surface for certain soil types has been hypothesised as the main influence on variability of residual deformation of plates subjected to subsurface explosions [29]. The DTP approach used in this manner, i.e. with DTPs at non-unique distances from the plate surface, can assess whether this non-uniform distribution of loading has an influence on localised plate deformation, which would be detected if significantly different impact times are recorded at the pins for nominally identical combinations of in-plane and lateral distance from plate centre. This may be a useful means for determining whether localised stress maxima and hence plate failure is more likely to occur for different soil conditions. Indeed, a suitable extension of the DTP method could be to record plate failure itself: whilst it is beyond the remit of the current work, it is possible that the DTPs could be primed to short once exposed to blast pressure or debris egress through a failed plate, thereby giving the time at which failure has occured. This can be used in conjunction with the displacement-measuring capability of the DTPs (pre-failure), however will make the DTPs effectively 'single use' for each test where failure occurs. This is acceptable given their low cost and ease of manufacture.

Numerical modelling was used in this study to determine the range of displacements in which to locate the DTPs. However, the relative ease of construction and installation of the apparatus suggests that the optimal arrangement can be determined from a series of preliminary tests using different DTP arrays when an accurate numerical model is not available, as is the case with more complex cases such as buried explosive events. Providing the DTP support system does not interact with the plate whilst deforming, or influence the blast event in any way, the DTP approach is a truly non-invasive means for measuring transient plate deformation and should not be limited to a specific range of charge mass and structural arrangement.

6. Conclusions

This paper presents a new method for measuring the dynamic deformation of explosively loaded plates. The design of displacement timer pins (DTPs) is detailed: small steel tubes located at pre-defined distances from the rear surface of an explosively loaded plate. A strain gauge on the perimeter of each pin will record a change in voltage when the plate comes in contact with the pin, and hence an array of DTPs can be used to determine the time at which the plate has displaced to certain values. This will the give the time-varying displacement of a small region of the plate which can be assumed to be equivalent to a single point value, i.e. mid-span in this article.

An experimental proof-of-concept test was conducted, with a 200 g spherical PE4 charge suspended 125 mm above the centre of a 4 mm thick steel plate. The steel plate had clear dimensions of 640×630 mm, and was clamped in the 640 mm span and unsupported in the 630 mm span. DTPs were used to record the time at which the centre of the plate had displaced 0, 10, 20, 30 and 40 mm, and the experimental data was compared with numerical displacements determined using LS-DYNA, where the blast was explicitly modelled and loaded the structure through fluid-structure interaction. The numerical and experimental results were in very good agreement. Therefore, the proposed experimental method has been proven in concept and offers an accurate and valuable means for determining the full-scale response of structures subjected to blast loads in aggressive environments.

The instrumentation is simple to construct, install and analyse. The comparatively low cost of the sensor components permits the DTPs to be effectively viewed as disposable, allowing deformation-time data to be gathered from situations that would otherwise not be considered suitable for instrumentation. DTPs are particularly valuable for situations where optical systems such as DIC/HSV or laser displacement gauges cannot be employed because of either proximity to the blast or field-of-view issues. In the particularly aggressive environment of shallow buried blast tests the proposed methodology may be used without further engineering of protection systems as measurement will generally be complete before the arrival of any debris.

Expansion of the proposed experimental method may allow the capture of higher resolution deformation-time profiles than the simple case presented herein. DTPs has a wide range of application and can be used with confidence as an inexpensive and robust measurement technique for use in full-scale blast testing.

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