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Structural response of corrugated plates under blast loading: The influence of the pressure-time history

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Abstract

The propagation of shock waves in confined environments is a complex phenomenon due to the potential for a multiplicity of reflections, diffraction and superposition of waves. The study of such wave propagation effects, which is different from the propagation of shock waves in free-field scenarios, is not entirely described in literature, especially when studying their influence on the response of structures. The analysis of such phenomena is of extreme relevance to the evaluation of protective structures to ensure the security of equipment and personnel. This paper studies the influence of shock wave related parameters on the mechanical response of simple structural elements. This is achieved through the analysis of the impulse train, multiple positive and negative pressure profiles and signal simplifications. This research uses the finite element code LS-DYNA to analyse the structural response sensitivity of a metallic plate to different parameters, when subjected to pressure data recorded from experimental tests. It is observed that the structural response is significantly influenced by the loading regime. Results indicate that the impulse has a significant effect on the deflection-time history of the structure in the impulsive regime and that the peak pressure and pulse duration affect the deflection response in the dynamic regime. It also shows that correctly defining the negative impulse train in the pressure-time history is one of the main factors leading to an accurate modelling of the mechanical response of the structure. It is also found that a complex and realistic pressure history profile can be reduced to a simplified pulse for structural analysis and design purposes.

Keywords: Blast load, impulse, pressure pulse, structural response, finite element analysis, LS-DYNA.

1. Introduction

The consequences of accidental explosions can involve severe damage of structures and loss of life. A considerable number of investigations on blast waves and their effects on structures can be found in the literature and blast loading of corrugated plates has been studied by several researchers with the aim of enhancing their resistance to blast. Such investigations predominantly focus on the response of structures subjected to idealised pulse loads (triangular) albeit with different magnitudes and pulse durations. Louca *et al.* [1] performed a parametric numerical study on load

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characteristics to determine the resistance of corrugated blast walls subjected to blast loading from a hydrocarbon explosion. They evaluated the structural response of the panel by varying the peak pressure and pulse duration, and concluded that for low pressure levels (2 – 5 bar) the structural response is insensitive to the duration of the pressure signal. For higher pressure values, however, an increase in the loading duration leads to an increase in the dissipated energy and, consequently, to earlier failure.

In the last two decades, a number of studies were performed to investigate the structural response of structures under different loading profiles, where only positive pressures were considered in the analyses, neglecting the negative part of the pressure signal. Florek and Benaroya [2] presented an extensive review on how pulse characteristics affect the structure of an aircraft subjected to an internal explosion. They show that the pulse loading shape has an important effect on the deformation behaviour of various structures so that the maximum deflection happens at different pulse durations for each peak load case. These authors also show that the peak pressure has a bigger impact on the structural response than the pulse duration. Huang *et al.* [3] studied pulse shape effects (*e.g.* rectangular, triangular and exponential) on underground structures subjected to external and internal blast loads and found that the pulse shape cannot be ignored in the damage analysis of buried structures. In 2016, Syed *et al.* [4] analysed the response of offshore blast walls subjected to high impulsive loading conditions. Their work has shown that the structural resistance is dependent on the combination of peak pressure and impulse applied to the structure. Sohn and Kim [5] explored the structural behaviour of corrugated blast walls under four different explosion loading shapes (rectangular, triangular, gradually applied and linearly decaying) and obtained results that indicate that the ductility ratio (the ratio of the maximum deflection and the deflection at the elastic limit) increases when higher pressures and longer pulse times are applied. Additionally, the effect of the natural period is reduced when higher pressures and impulses are observed. The results also indicated that, in the impulsive domain, the applied impulse is more relevant than the peak pressure and the load duration separately. Tan *et al.* [6] performed numerical analyses to evaluate pulse shape effects on the fire and blast resistance capabilities of steel beams and observed that the blast and fire resistance of the studied components sequentially decreases under the action of exponential, triangular and rectangular loading profiles.

It is known from a number of studies in literature that structures are subjected to different blast loading profiles depending on the environment where the explosion occurs. Rose and Smith [7] focused their attention on the effect of confinement of urban roads on the positive and negative phase impulses of blast waves. They observed that road width and building height increase the positive phase impulse, while the negative phase impulse is not heavily affected. Remennikov and Rose [8] demonstrated the importance of considering adjacent structures when determining the blast loads on buildings in urban environments. Their results show that a significant underestimation of the blast response can occur if the presence of the surrounding buildings is neglected in the blast analysis. These authors also concluded that the negative phase of the blast pulse may have an influence on lightweight facade panel behaviour by causing the facade material to fail outward. Geretto *et al.* [9] experimentally studied steel plates under blast loads using three different confinement arrangements: free-air burst, fully vented and fully confined. Their observations and results

indicate that the structural response depends on the level of confinement. They also found that the fully confined geometry is equivalent to approximately four times the blast load generated by an equivalent explosive mass in an unconfined blast. Additionally, the impulse generated in a fully vented configuration was observed to be approximately three times more severe than in free-air conditions.

Krauthammer and Altenberg [10] observed that both positive and negative phases of the pressure curve, and their interaction with the structure, might influence the structural behaviour. The main focus of their work was the assessment of negative phase effects, which are often ignored in blast analyses, on glass panels subjected to blast waves using different scaled ranges and charges. These authors have shown that the inclusion of the negative phase causes large motions of the glass panel studied toward the incoming blast loading. These authors observed that this phenomenon happens normally for small overpressures, when the impact of negative phase becomes considerable. To better understand the interactions and the respective propagation of reflected shock waves, Sauvan *et al.* [11] conducted an experimental study to evaluate the variation of blast parameters, such as overpressure, impulse and time of arrival, by progressively adding walls to build a confined compartment around the explosive charge. One of the major findings was that in a semi-confined environment, the negative phase of the blast wave can lead to more significant damage than the positive phase.

In 2014, Rahman *et al.* [12] conducted a numerical analysis to understand the structural response of blast walls under blast loading, stating that a simplified blast load cannot be used to represent the realistic behaviour of structures. Kang *et al.* [13] performed a structural response analysis of structures under blast loads with respect to the magnitude of overpressure and impulse in both positive and negative phases. They found that the negative phase of a blast wave is highly dependent on geometrical conditions and negative pressures should be included in blast analyses to obtain accurate structural response.

The study of wave propagation in confined environments, which is different from the free-field propagation of shock waves, is not fully described in scientific work, specially when it relates to the response of structures. The aim of this work is to investigate the structural response of a corrugated steel panel member subjected to different pressure profiles. For this purpose, a series of numerical simulations are performed to study the effect of the shape of the pressure curve on the structural response. This paper presents a numerical analysis of a single structure to evaluate the influence of several wave related parameters on its structural response, *i.e.* impulse train, complex pressure profiles and signal simplifications.

2. Numerical modelling

The finite element models of the corrugated structures are described in this section and all numerical simulations were performed using LS-DYNA. The dynamic pressure curve was applied as a uniformly distributed load on the corrugated section and its direction is normal to the surface, as shown in Figure 1(b). As the tested corrugated panels are symmetric, only one half of a corrugation is modelled, along its full height. Connection structural elements are

incorporated into the model at each end of the span to better describe the real structure. Figures 1(a) and 1(b) show a schematic drawing of the test panel and its dimensions. The components of the numerical model are shown in detail in Figure 1(c).

The corrugated plate is modelled using four-node fully integrated shell elements and the connections are described by eight-node solid elements with a single integration point, leading to a total of 37,408 elements. Additional symmetry conditions were applied on the two lateral edges along the length of the corrugated plate and the steel work component was fully constrained on its bottom face (see Figure 1(c)).

Figure 1: Geometrical and numerical details of the test panel: (a) profile dimensions (cross-section), (b) side view and (c) assembly of the FE model.

The interaction between the corrugated plate and the supporting frame are defined through appropriate contact

conditions. The contact between the components was modelled through tied contact algorithms to simulate the connections as welded. The contact *AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK was used to model the connection between the steel work and the flexible angle as well as the angle component with the flexible angle part, as such algorithm accounts for the compression and tensile forces transmitted through such connection. Additionally, the interaction between the corrugated plate and the angle component was implemented using the contact type *TIED_SHELL_EDGE_TO_SURFACE. This allows the edge nodes of the corrugated plate to be tied to the angle component without prejudice of their rotational degrees-of-freedom [23].

2.1. Constitutive material modelling

Stainless steel is often employed in the manufacturing of corrugated panels. In this work, the structural response of the component is described by an elasto-plastic model, where stress-strain and a strain rate dependency functions are defined [15]. The material model used is *MAT_PIECEWISE_LINEAR_PLASTICITY (*MAT_024 in LS-DYNA), and the relevant material properties are the density (ρ), Young's modulus (E), Poisson's ratio (ν) and yield stress (σ_y). A detailed stress-strain curve is also included to accurately define the material response. Additionally, and as reported by Langdon and Schleyer [16], the effect of strain rate should be considered in dynamic structural analyses since the dynamic pressure loading resulting from an explosion induces high strain rates in the material. The strain rate sensitivity of steel can be accounted for with the Cowper-Symonds model [17]. The relation suggested by Cowper and Symonds indicates a scaling of the yield stress as

$$\sigma_y = 1 + \left(\frac{\dot{\epsilon}}{C} \right)^{\frac{1}{p}}, \quad (1)$$

where $\dot{\epsilon}$ is the strain rate and C and p are curve-fitting material constants. The material properties used in this model are listed in Table 1.

Table 1: Material properties used in the finite element modelling [18].

Component		Corrugated plate	Angle	Flexible angle	Steel work
Material		AISI 316L	AISI 316L	AISI 316L	Mild steel
Density	ρ [kg/m ³]	7,970	7,970	7,970	7,970
Young's modulus	E [GPa]	200	200	200	205.8
Poisson's ratio	ν	0.3	0.3	0.3	0.3
Yield stress	σ_y [MPa]	293.7	283.3	276.2	235
Scaling constant	C [s ⁻¹]	1,522	2,720	429	40.4
Scaling constant	p	5.13	5.78	4.08	5

2.2. Finite element discretisation analysis

This section looks at the effect of the element size on the quality of the results. A two-step mesh convergence study was performed to obtain an optimal element size for individual structural components. Firstly, a mesh convergence study was done on the supports of the corrugated panel. Element sizes of 3, 2, 1.5 and 1 mm were tested, for an element size of the corrugated plate of 17.5 mm. The maximum deflections at the midpoint of the corrugated plate for the corresponding element size are listed in Table 2. The corresponding normalised relative values are plotted in Figure 2, where clear convergence is observed. An element size of 2 mm was considered to be an ideal compromise between computational time and the quality of the results. Note that for smaller element sizes no significant changes in the deflection are observed.

The second stage of this analysis, element sizes of 17.5, 8.8, 4.4 and 2.2 mm were used on the corrugated plate, under similar loading conditions. The maximum element size that can be used is 17.5 mm due to the dimensions of the corrugation profile. It was found that the maximum variation of the maximum deflection of the plate considering the specified mesh sizes was only 6% when comparing the coarser and finer meshes, which indicates that choosing the former to perform further numerical simulations is a reasonable choice since it does not compromise computational efficiency. This can be seen from the values listed in Table 2 and the results in Figure 2.

Table 2: Maximum deflection on the corrugated plates for the two-stage mesh convergence analyses.

Supports				Corrugated plates			
Test	Size [mm]	# Elements	Deflection [mm]	Test	Size [mm]	# Elements	Deflection [mm]
S1	3.0	8,886	18.2	C1	17.5	37,408	12.0
S2	2.0	37,408	12.8	C2	8.8	38,092	11.6
S3	1.5	69,492	12.4	C3	4.4	40,524	11.4
S4	1.0	297,668	11.8	C4	2.2	50,556	11.3

3. Results and discussion

This section covers the validations of the proposed models described above, and the detailed analysis of the effects of pressure pulse parameters on the structural response of the corrugated panels.

3.1. Validation of Finite Element Analysis

Experimental results by Schleyer *et al.* [14] on the response of a 1/4 scale stainless steel corrugated structure under pulse pressure loading were used to validate the model that will be used to study the influence of the pressure profile on the response of the structure. These experiments were carried out using a pulse pressure loading rig (PPLR), designed at the Impact Research Centre of the University of Liverpool. The set-up of the PPLR, shown in Figure 3, consists of

Figure 2: Normalised maximum deflection on the corrugated plates for the two-stage mesh convergence analyses, as a function of the normalised element count.

a support plate with a clamping frame positioned between two pressurised chambers. When testing specimens under dynamic loads, the two chambers are pressurised simultaneously to ensure that both compartments have the same pressure and are in equilibrium. Afterwards, depending on the intended loading direction, one of the diaphragms is ruptured causing a differential pressure across the specimen. Finally, the second diaphragm is burst and the pressure is vented to the atmosphere.

Figure 3: Schematic representation of the pulse pressure loading rig (PPLR, adapted from [14]).

The dynamic pressure pulse generated by the PPLR was idealised as a triangular shape curve with the same impulse and peak pressure of the real pulse. The shape of the blast loading pulse in Figure 4, with a peak overpressure ($P_{\max}$), a duration time (t_d) and a rise time ($t_{\max}$), was considered.

Figure 4: Idealised triangular pressure pulse.

The numerical displacement-time history and the experimental results are compared in Figure 5. It should be noted that no damping was applied to the FE model, which is the main reason for the model vibration around the final deformation state. The maximum and permanent deflections, $\delta_{\max}$ and δ_{per} , respectively, are listed in Table 3.1, along with the relative differences to the experimental results. The centre of the corrugated plate is taken as the monitoring point. The maximum deflection was defined as the maximum value of the deflection-time history and the permanent deflection was taken as the average value between the maximum and the minimum wave height of the final state of deflection. A good overall agreement with experimental data can be observed in these results. The permanent deflection of the plate is captured by the FE model with a relative error lower than 10%, when compared to the experimental results, and a well predicted time to maximum displacement is also achieved. The computed peak deflection is, however, 33% higher than the experimental value. This is thought to be related to the simplification adopted for the load application to numerically represent the decompression of a pulse pressure loading rig to induce deformation on the plate. Additionally, sealing arrangement used in the experiments may have provided additional restraint to the movement of the blast walls, which can also explain the global curve of numerical deflection to be slightly higher than the experimental recordings. Nevertheless, validation of the model has mainly focused on the residual deflection, which does not affect the validity of the further research since most of the analysis are made based on the comparison of steady state stages of deflection.

Table 3: Details of the pressure profile applied on the corrugated plate and comparison of the computational and experimental results [14] of the maximum and permanent deflection parameters.

$P_{\max}$ [kPa]	$t_{\max}$ [ms]	t_{dur} [ms]	$\delta_{\max,\text{exp}}$ [mm]	$\delta_{\max,\text{num}}$ [mm]	Error [%]	$\delta_{\text{per},\text{exp}}$ [mm]	$\delta_{\text{per},\text{num}}$ [mm]	Error [%]
97	33.9	63.0	9.3	12.4	33.3	2.0	1.8	10.0

Figure 5: Time-history of the mid-span deflections: Numerical results and experimental measurements by Schleyer and Langdon [14] data.

3.2. Parametric analysis on the behaviour of a corrugated plate

Blast load pressure profiles differ according to the type of explosion and its confinement level [13]. Due to this variability, a good understanding of how the response of a structure depends on the pressure profile is needed. In this section, the structural response of the single corrugated plate described above is evaluated using different load profiles. The work is divided in two main parts: the influence of different parameters concerning experimental pressure signals measured by Caçoilo *et al.* [19] in a confined environment such as survival shelters, and the possibility to simplify those signals according to their total impulse.

The type of response of a structure in a blast scenario is related to its natural period (T) and to the duration of the event (t_0) [20]. Three loading regimes can be defined according to Mays and Smith [20]: (i) impulsive loading, (ii) dynamic loading and (iii) quasi-static loading. In the impulsive regime the load pulse is short compared to the natural period of vibration of the structure,

$$wt_0 < 0.4 \quad \left[\infty \frac{t_0 \text{ (short)}}{T \text{ (long)}} \right] \Rightarrow \text{Impulsive load,} \quad (2)$$

while in the dynamic regime the load duration and structural response times are similar,

$$0.4 < wt_0 < 40 \quad \left[\frac{t_0}{T} \approx 1 \right] \Rightarrow \text{Dynamic load.} \quad (3)$$

In the quasi-static regime the load duration is long, compared to the natural response time of the structure,

$$40 < wt_0 \quad \left[\infty \frac{t_0 \text{ (long)}}{T \text{ (short)}} \right] \Rightarrow \text{Quasi-static load.} \quad (4)$$

where $w = 2\pi/T$ is the natural vibration frequency of the structure. For impulsive loading, most of the deformation will occur after the blast load has ended, whereas for quasi-static loading, the blast will cause the structure to deform whilst the loading is still being applied [20]. With this in mind, this work focuses on the impulsive and dynamic

loading regimes and it is thus necessary to perform a modal analysis to investigate the natural frequency and the corresponding vibration modes of the structure [21].

From this analysis, the first mode is related to the bending mode response, with a natural vibration period of 7.36 ms. Figure 6 shows this bending mode shape. The analysis was conducted to obtain the natural period of the structure and, consequently, define the loading application time ranges correspondent to each domain. Using the intervals described above for the different load regimes, the loading time ranges were determined to be $t < 0.46$ ms to ensure the analysis is in the impulsive domain and $0.46 < t < 46$ ms for the dynamic regime. This determination is useful to ensure that the duration of the applied loads lies within each of these domains. Consequently, two sets of simulations can be done to understand the influence of the loading regime on the behaviour of the corrugated plate.

Figure 6: First mode shape of the corrugated panel model (135.79 Hz).

3.2.1. Pressure profile impact analysis

Complex pressure profiles can be described by a combination of parameters such as the peak pressure, the loading time and the generic shape of the profile. The influence of these parameters on the structural response of the corrugated plate is evaluated in this section. The load application time, the first positive peak, multiple positive and negative peaks are here studied by considering the dynamic and impulsive domains for elasto-plastic behaviour. It should be noted that original pressure-time histories are numerically modified by multiplying the original signal by a factor that

induces the response to be in each of the desired domains.

The first part of the study aims to understand the relevance of multiple pressure peaks to the structural response, instead of a single peak, typically from a free-air explosion, in both dynamic and impulsive domains. To dissociate the influence of the several parameters described above, three individual scenarios were tested, considering the same original pressure-time history: the application of partial pressure signals to evaluate the influence of the recording time, typically defined by user experience (see Figure 7(a)); the application of two segments of the same pressure signal, meeting the same absolute impulse value but opposite signs (see Figure 8(a)) and; three segments of the same pressure signal with the same total impulse (see Figure 9(a)). The different pressure profiles and corresponding deflection-time histories are shown in Figures 7(b) and (c), Figures 8(b) and (c) and Figures 9(b) and (c) present the corresponding response for the several cases.

Regarding the first scenario, and considering the results shown in Figures 7(b) and 7(c), it can be seen that the permanent deflection is different for the three cases in both the impulsive and the dynamic regimes. The permanent deflection is the average between the maximum and minimum wave height of the steady state stage of the deflection-time history. It can be seen in Figure 7(b) that successive peaks, which are approximately 50% lower than the main overpressure peak, are still relevant to the final structural behaviour since the permanent responses vary between -35.9 and -59.4 mm. In the impulsive domain, the responses also differ, varying between -1.8 and -34.6 mm, as shown in Figure 7(c). As the total specific impulse is dependent on the duration of the measured pressure-time history, it can be concluded that the loading time, as well as the multiple positive and negative peaks, are important to the permanent deflection of the structure, even if these are 87% smaller than the first overpressure peak.

Regarding the effect of positive vs negative impulse components on the behaviour of the plate, for similar absolute impulses, corresponding to the second scenario studied, two different signals result from the trimming of an original signal so that the resultant signals have the same absolute specific impulse but opposite signs are applied to the structural component. A first profile has a total impulse of 279 kPa.ms while the other has -279 kPa.ms, as can be seen in Figure 8(a). Although the same absolute total impulse is applied, the permanent deformation is different for both the dynamic and the impulsive domains. The permanent deflection for the dynamic regime is 10.2 mm when the negative total impulse is applied whereas for the positive case this is approximately -61.9 mm, which represents an absolute difference of 607% and change in direction, as shown in Figure 8(b). Under impulsive loading, the results in Figure 8(c) show that, although the absolute permanent deflections are similar, they are in opposite directions. A total deflection of 15.7 mm is calculated when the total impulse is negative and -27.3 mm when the applied load has a positive impulse. This means that a negative impulse leads to the suction of the plate in the direction opposite of the blast wave propagation. In both regimes the magnitude of the permanent deflection is attenuated for total negative impulses since the deflection is smaller for these cases. This leads to the unequivocal conclusion that, when considering the structural response, the sign of the impulse is as important as its magnitude.

Finally, a comparison is also made between three different pressure signals (see Figure 9(a)) with the same specific total impulse and different duration times, which are extracted from the same overpressure-time history, as defined by

(a) Dynamic and impulsive regimes

(b) Dynamic regime

(c) Impulsive regime

Figure 7: Effect of the loading time: (a) overpressure-time history for both regimes, deflection-time history in (b) the dynamic regime and (c) the impulsive regime.

(a) Dynamic and impulsive regimes

(b) Dynamic regime

(c) Impulsive regime

Figure 8: Effect of the overpressure profile shape for a constant impulse of 279.3 kPa.ms: (a) overpressure-time history, deflection-time history in (b) the dynamic regime and (c) the impulsive regime.

the third scenario stated above. This study was performed to analyse how the structural behaviour might change for pulses with different number of pressure peaks for a constant total impulse. From the results shown in Figure 9(b), taking the recording times of 26, 18 and 6 ms are -43.1 , -15.5 and -46.4 mm, respectively. Although the blue and black curves present a similar final state response, overall the response is different even when the applied specific impulse is the same. By contrast, deflection-time histories and permanent deflection in the impulsive regime are similar and about -1.6 mm, as can be seen in Figure 9(c). These results indicate that the specific total impulse is the main parameter responsible for the structural response in the impulsive regime.

The pressure-time history of a free-air explosion can be simplified to the corresponding positive peak, neglecting the consecutive negative phase [22]. In literature, however, there is a lack of studies based on complex pressure-time histories, as the ones analysed here. To better understand the impact of applying a simplified pressure-time signal on the structural response, different pressure profiles were evaluated. On a first instance, the verification consisted in comparing the response of the plate with either the total experimental profile obtained from small-scale experiments or only the first positive peak of the same profile, as shown in Figure 10(a), similarly to what is commonly done in free-air explosions. Figures 10(b) and 10(c) show the corresponding deflection for the dynamic and impulsive regimes, respectively. It can be seen for the dynamic case that from approximately 4.3 ms onward the response differs since from that time the pressure profiles are also different. The maximum deflection is -36.1 mm when the total experimental signal is applied and -198.1 mm when only the first positive peak is considered. This demonstrates that successive peaks significantly influence the structural response, in this case reducing the final deformation of the plate. The permanent response is also different under impulsive loading. The deformation of the plate when subjected to either the experimental signal or the first positive peak only is -1.2 mm and -198.7 mm, respectively. As such, using the first pulse peak, as is often done in similar analyses, is not a reasonable simplification and leads to unreliable results.

The negative pressure peaks in the overpressure signal is also assessed to verify its impact on the structural behaviour. To achieve this, a new pressure profile was obtained by neglecting all negative phases, as shown in Figure 11(a). From the results in Figure 11(b), it can be seen that the permanent deformation is now -477.2 mm, compared to -35.3 mm when the whole signal is considered. In the impulsive regime, the deflection is -448.7 mm when positive pressures are used, whereas if the plate is subjected to the total pressure profile, the final deflection is -1.2 mm, as shown in Figure 11(c). Consequently, the negative phase has an effect that cannot be neglected on the blast performance of a structure for both the dynamic and the impulsive loading regimes. Additionally, pulse shape effects cannot be ignored. In conclusion, when the plate response lies within the impulsive domain, it is noticed that its structural behaviour is mainly controlled by the magnitude of the applied impulse.

3.2.2. Simplifications based on the total impulse

In this section, the accuracy of triangular pulse loads as simplifications of actual pressure signals, keeping the same total specific impulse, is assessed through the analysis of the blast resistance of corrugated plates.

(a) Dynamic and impulsive regimes

(b) Dynamic regime

(c) Impulsive regime

Figure 9: Effect of loading time for a constant impulse of 55.1 kPa.ms: (a) overpressure-time history, deflection-time history in (b) the dynamic regime and (c) the impulsive regime.

(a) Dynamic and impulsive regimes

(b) Dynamic regime

(c) Impulsive regime

Figure 10: Comparison between the application of the entire pressure profile versus the first positive peak for the dynamic and impulsive regimes: (a) overpressure-time history, (b) and (c) corresponding deflection-time history.

(a) Dynamic and impulsive regimes

(b) Dynamic regime

(c) Impulsive regime

Figure 11: Comparison between the application of the total pressure load versus the positive phase for the dynamic and impulsive regimes: (a) overpressure-time history, (b) and (c) corresponding deflection-time history.

A first analysis was conducted to assess the effect of simplifying the pressure profile in the dynamic regime on the structural response. The applied triangular load, shown in Figure 12, is described by a peak overpressure $P_{\max}$ (corresponding to the first positive peak of the experimental signal) and the pulse duration t_d , calculated such that the area of the triangle corresponds to the total specific impulse of the original signal, shown in Figure 13(a). The results in Figure 13(b) demonstrate that the structural response is significantly different — the deflection corresponding to the application of the original profile is -55.8 mm while for the simplified triangular profile is -4.1 mm. As such, it is not reasonable to apply a simplified load pulse in the dynamic domain. This might be explained by the fact that the load application time is of the same magnitude as the period of oscillation, which induces the successive positive and negative pressure peaks to play independent roles in the direction of movement of the structure, due to the application of intermittent pulse loads.

Figure 12: Idealised triangular pulse shape load, where the area under the curve represent the total specific impulse acting on the plate.

The same approach was also used to evaluate the component's structural response under impulsive regimes, for total positive specific impulses. The corresponding results are shown in Figure 14(a) and (b). As it can be seen, such simplification predicts reasonably well both maximum displacement and period of oscillation. Nevertheless, aiming to understand the sensitivity of the predictions, a number of cases with increasing total specific impulse are evaluated, as plotted in Figures 14(c-h), where the specific impulse values were carefully selected to obtain a realistic plastic deformation of the selected structural member. As an example, the displacement over the time for the test applying a total specific impulse of 75.1 kPa.ms is shown in Figure 14(d). Although the responses seem to be identical, the oscillation period ($T_{\text{Exp}} = 7.2$ ms vs $T_{\text{Idealtriang}} = 7.7$ ms) and the positive amplitude peaks of the signals are distinct ($A_{\text{Exp}} = 3.7$ vs $A_{\text{Idealtriang}} = 7.3$).

Similarly, the simplification of pressure signals with total negative specific impulses is tested, assuming that the first peak of the pressure signal is represented by an initial positive idealised triangle (with the same overpressure and impulse of the original signal), while a second inverted triangle represents the remaining specific impulse. The structural plate was here subjected to four different pulses with increasing total negative specific impulses, as shown in Figures 15(a, c, e, g). The corresponding displacement-time histories are shown in Figures 15(b, d, f, h). In general,

(a)

(b)

Figure 13: Effect of simplified vs total pressure profile (where $i_{t, \text{exp}}$ is equal to $i_{t, \text{idealised triangle}}$) on the structural response for the dynamic domain: (a) overpressure-time history and (b) deflection-time history.

In general, very good agreement is observed between the responses of both pressure curves applied to the corrugated plate. Specifically, for a total specific impulse of -276.6 kPa.ms , the mid-span deflection-time history is shown in Figure 15(h). Here, the simplified and the original response are identical, with exactly the same oscillation period ($T_{\text{Exp}} = T_{\text{Idealtriang}} = 7.4 \text{ ms}$).

Table 4 lists the applied impulse, the mid-span displacement, which corresponds to the first oscillation of the deflection-time history, for both the original and the idealised triangular loads, and the corresponding relative error. Interestingly, it can be seen that the relative error decreases with the increase of the total impulse, *i.e.* the response due to the original and the idealised triangular loads becomes closer for higher values of specific impulse. For instance, the error of the first peak displacement considering an applied impulse of 28.6 kPa.ms is 31%, while for an impulse of 178.9 kPa.ms , the error is close to zero. A similar trend is observed for negative impulse values.

(a) $i_t = 28.6$ kPa.ms

(b)

(c) $i_t = 75.1$ kPa.ms

(d)

(e) $i_t = 105.5$ kPa.ms

(f)

(g) $i_t = 178.9$ kPa.ms

(h)

Figure 14: Comparison between the application of the original pressure load and the idealised triangle for different positive total specific impulse for the impulsive domain: (a), (c), (e), (g), (i) overpressure-time history and (b), (d), (f), (h), (j) corresponding deflection-time history.

(a) $i_t = -34.4$ kPa.ms

(b)

(c) $i_t = -90.3$ kPa.ms

(d)

(e) $i_t = -131.5$ kPa.ms

(f)

(g) $i_t = -276.6$ kPa.ms

(h)

Figure 15: Comparison between the application of the original pressure load and the idealised triangle for different negative total specific impulse for the impulsive domain: (a), (c), (e), (g), (i) overpressure-time history and (b), (d), (f), (h), (j) corresponding deflection-time history.

283 A comparison of the relative error as a function of the total specific impulse with varying thickness of the cor-
 284 rugated plate and, consequently, the stiffness of the component, is shown in Figures 16(a) and 16(b). The relative
 285 error was calculated taking into consideration the area under the mid-span deflection-time history. The relative error
 286 decreases as higher impulses are applied. From the linear curve fitting method presented in Figures 16(a) and 16(b),
 287 it can be concluded that there is no obvious relation between the plate thicknesses (i.e. structural stiffness) and the
 288 total specific impulse. The suggested approach, however, can be used to determine the elasto-plastic responses of the
 289 steel plate for different loading profiles. The simplification of the pressure-time history, however, is accurate only in
 290 the impulsive domain, for an equivalent total transferred impulse.

(a)

(b)

Figure 16: Structural response relative error with (a) increasing positive and (b) increasing negative specific impulses for complex-to-simplified pressure-time histories.

Table 4: First peak deflection due to a simplified triangular vs original load pulse, for different impulse values.

i_t [kPa.ms]	δ [mm] (Original load)	δ [mm] (Triangular load)	Error [%]
28.6	-4.2	-3.2	31.3
75.1	-8.0	-7.5	6.7
105.5	-11.3	-10.3	9.6
178.9	-20.9	-19.8	5.6
-34.4	1.7	1.5	13.3
-90.3	6.9	6.6	4.5
-131.5	11.9	11.5	3.5
-276.6	29.6	29.1	1.7

4. Conclusions

The dynamic response of a corrugated plate under dynamic and impulsive pressure loading is investigated in this paper. A numerical model is proposed to analyse the influence of the impulse train, complex pressure profiles as well as signal simplifications on the structural response of corrugated plates. The proposed model is based on the finite element method (LS-Dyna) and a number of different studies are done to analyse the deformation behaviour of metallic plates when subjected to pressure data recorded experimentally.

It is observed that the structural response is significantly influenced by the loading regime — dynamic or impulsive. The blast strength of the corrugated plate is sensitive to parameters of the loading curve, such as the impulse, the peak pressure and the duration of the pulse. This is also shown to have a significant effect on the deflection-time history of the structure. The presence of multiple positive and negative peaks is also shown to have an effect on the structural response. Ignoring the successive positive as well as negative peaks after the first one is a simplification which leads to unreliable deformation results.

The main observations and conclusions of this study indicate the reliability of transforming a complex pressure signal into a simplified triangular shape with the same total transferred impulse, as suggested in this paper, in accurately capturing the behaviour of a corrugated plate under blast loading. The proposed method was used to simplify pressure profiles from confined environments and proved to be able to simulate the structural response of corrugated steel plates under the simplified curve in the impulsive domain. In the dynamic domain it is not possible to adapt the same simplified loading pattern. This is related to the fact that the load application time is of the same magnitude as the period of oscillation, inducing the successive positive and negative pressure peaks to play an active role in the direction of movement.

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