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A new general approach to derive normalised pressure impulse curves

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ABSTRACT

A pressure impulse (PI) diagram is an important tool used for the preliminary design of structural members against blasts. Normalised PI diagrams can be derived using single degree of freedom (SDOF) theory to quickly determine the PI diagram of a given structural member. In order to use PI diagrams for blasts occurring in various confined environments, characterised by irregular shaped pulse loads, an investigation into the effects of pulse shape on a given point on the normalised PI curve is undertaken. Relying on the concept of the effective pulse load, three parameters which define the shape of the effective pulse load are determined. These parameters are then used to derive a method for determining a point on the normalised PI curve for elastic, rigid plastic and elastic plastic hardening structural members. The overall procedure can be iterated to determine many points, thus forming the entire normalised PI curve. Due to the generality of this new approach, it can be applied to structural members subjected to any arbitrary pulse load as long as its response and failure are controlled by its flexural behaviour.

1. Introduction

The SDOF method is a first order method used to model the response of structural members, such as reinforced concrete (RC), steel members and unreinforced masonry walls, against blasts based on an anticipated response mode [1–3]. Its applications can even be extended to that of structures against sonic booms [4] and aircraft structures against blasts [5]. ASCE guidelines [6,7] and the most recent guidelines of UFC-3-340-02 [8] all recommend the use of the SDOF method for such analyses. The SDOF method models the deflection of an important point on the structural member, for example the mid span of a simply supported beam, by simplifying it into a lumped mass on a spring type system. Therefore, the method relies on certain parameters, such as the equivalent mass and the resistance deflection ($R\Delta$) function of the idealized spring system [9–11].

Using the SDOF model, pressure impulse (PI) curves for structural members can be determined. Provided that the parameters used in the SDOF model accurately predict the response of a given structural member, the PI curve can be used to quickly determine whether the member fails or survives a given blast [12–14]. Therefore, it can be used as a preliminary design tool for structural members against blasts. A normalized PI curve represents a family of PI curves and can be converted quickly into a PI curve for a given structural member. This is done using expressions for the minimum impulse and the minimum peak reflected pressure asymptotes. For this reason, it is recognized as a useful tool for analysis.

Krauthammer et al. [15] and Li & Meng [16] undertook a dimensional analysis on PI curves for elastic members subjected to different pulse loads in order to investigate the effects of pulse shape on the normalized PI curve. This analysis was undertaken for a load function which is typically used for external blasts in which the parameters can be manipulated to form three pulse shapes; exponential, triangular, and rectangular. Li & Meng [16] then attempted to eliminate the effects of pulse shape on the normalised PI curve for elastic members. Two parameters, n_1 and n_2, were introduced which were empirical functions of the geometric centroid of the pulse load. These parameters were then part of a general hyperbolic function which describes the normalised PI curve for any elastic member subjected to any pulse load shape. This empirical approach for eliminating the effects of pulse shape was proven to be very efficient and accurate for the pulse load shapes tested in the study which are typically associated with external blast loads. However, Campidelli & Viola [17] attempted to extend those empirical equations to be more applicable to a wider range of pulse shapes. They found that for some pulse shapes, the errors involved in those empirical equations were quite significant. This suggests that the empirical approach contains limitations, one of which is that the shape of the pulse load was defined by a single parameter which was labelled d. Another limitation of this

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empirical approach is that within different regions of a PI curve the shape of the pulse load acting on the structural member, from the time at which the shockwave reaches the member until the time at which the member reaches its maximum deflection, changes. This is due to the relative relationship between the load function and the structural response which is unique for each point along the normalised PI curve [15]. Therefore, by assuming that the shape of the elastic normalised PI curve can be described by a single parameter, *d*, which is calculated from the pulse load shape, does not take the changing load–response relationships into consideration.

Fallah & Louca [2] attempted to extend the studies conducted by Krauthammer et al. [15] and Li & Meng [16] by deriving normalised PI curves, using a dimensional analysis, for an SDOF system with a bilinear resistance deflection ($R\Delta$) function. The bilinear $R\Delta$ functions investigated were elastic plastic hardening and elastic plastic softening. Idealising the response of an RC or steel structural member using a bilinear $R\Delta$ function is much more appropriate as the yielding and ductility of such a member are taken into account. As done by previous studies, normalised PI curves for such members subjected to pulse loads typically associated with external blasts, that is, exponential, triangular and rectangular shapes, were derived, as they corresponded with that of external blasts. However, for more abstract pulse shapes, the entire approach needs to be repeated and new differential equations need to be solved to derive their associated normalised PI curves.

To date, all studies conducted on normalized PI curves have only investigated pulse load shapes corresponding to blasts in an external environment. However, blasts can also occur in a confined or partially confined environment in which shockwave reflections off surrounding walls can occur. This can cause pressure time histories with abstract pulse shapes to act on surrounding structural members. Although there is a high level of variability associated with such blast load scenarios, the most recent guidelines of UFC-3-340-02 [8] claim that it is appropriate to simplify a confined blast pressure time history to a bilinear pulse load. Dragos et al. [18] also support this claim but provide a different technique for obtaining such a simplified bilinear pulse load. Therefore, normalised PI curves derived for these simplified bilinear pulse load shapes will facilitate the quick determination of the response of structural members against confined blasts. However, due to the abstract shapes associated with the simplified bilinear pulse load, a thorough understanding of the effects of pulse shape on the normalized PI curve should be established.

In the current study, a new approach for deriving a normalised PI curve for any pulse load shape and any bilinear elastic plastic hardening $R\Delta$ function shape is provided. Firstly, the effective pulse load (defined differently to that of Youngdahl [19]), as opposed to the actual pulse load, is investigated and discussed. This is because the concept of the effective pulse load is the foundation of this new approach. Then, by undertaking an approach similar to Li & Meng [16] and Fallah & Louca [2], a database of many points on the normalised PI diagram is determined for various different $R\Delta$ functions and effective pulse shapes. Then, parameters which define the shape of an effective pulse load are derived. These parameters, in conjunction with the database of values, are then used as the basis to derive the formulae so as to determine a single point on the elastic and rigid plastic normalised PI curves. Furthermore, using the database, the formulae for determining a single point on the normalised PI curve for a member with a bilinear $R\Delta$ curve are also derived. Even though the current study provides a methodology for determining a single point on the normalised PI curve, it can be repeated to find many points, thus forming the entire normalised PI curve. Also, due to the generality of this approach, it can be applied to any pulse load shape. Finally, the overall approach to determine a normalised PI curve utilising a spreadsheet tool with the formulae derived in the current study, is outlined. Such a spreadsheet can be created rather quickly leading to the efficient analysis of structural members against blast load scenarios which generate more abstract pulse load shapes, such as that predicted by UFC guidelines [8] for confined blasts. This approach is more suitable to practicing engineers who do not wish to use a full finite element approach due to its long simulation times and specialised knowledge required.

2. Normalised pressure impulse curves

For the purposes of this study, a normalised PI curve, as shown in Fig. 1, is defined as a PI curve with horizontal and vertical asymptotes equal to unity, as seen by the horizontal and vertical dashed lines, respectively. Studies conducted on PI curves, such as Krauthammer et al. [15] and Li & Meng [16], have shown non-dimensional PI curves for elastic members in which the magnitude of the horizontal and vertical asymptotes are equal to 0.5 and 1, respectively. However, the coordinates of any non-dimensional PI curve can be manipulated to make both of its asymptotes equal to unity, thus forming a normalised PI curve. Fig. 1 shows that the coordinates of any normalised PI curve are I/I_{min} and $P_{\text{r}}/P_{\text{rmin}}$. To convert a normalised PI curve to a PI curve of a given structural member, the axes, and thus the coordinates, should be multiplied by I_{min} and P_{rmin}. For a given $R\Delta$ curve of a structural member, the equations for I_{min} and P_{rmin} can be determined using the law of conservation of mechanical energy [2]:

$$I_{\text{min}} = \sqrt{2ME_{\text{R}}} \tag{1}$$

$$P_{\text{rmin}} = \frac{E_{\text{R}}}{y_{\text{m}}} \tag{2}$$

where M = equivalent mass; y_{m} = maximum deflection; and E_{R} = strain energy, or: $E_{\text{R}} = \int_0^{y_{\text{m}}} R(y)\text{d}y$, in which $R(y) = R\Delta$ function.

Fig. 1 also displays the three different regions, or load–response relationships, of the normalised PI curve. The regions are the impulse controlled region, the dynamic region and the quasi-static region. Fig. 2 displays examples of the interaction between the load time history and the deflection time history for all three load–response relationships; impulse controlled (a), dynamic (b) and quasi-static (c). For each load–response relationship, the duration of the load, t_{d}, and the time to reach maximum deflection, t_{max}, are also illustrated.

The relationship between t_{max} and t_{d}, in Fig. 2, indicates the main notion which distinguishes the three load–response relationships from each other. As shown, for the impulse controlled

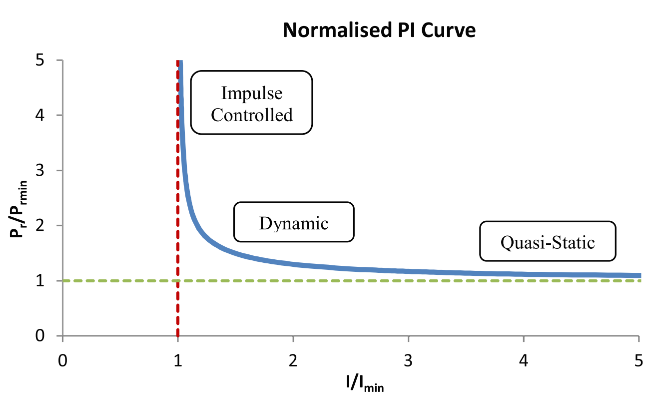

Fig. 1. Normalised PI curve for elastic member subjected to triangular pulse load.