

ASSESSMENT OF A SIMPLIFIED METHODOLOGY FOR PRELIMINARY BLAST-RESISTANT DESIGN OF INSULATED PRECAST CONCRETE WALL PANELS

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Abstract

A Blast loading history can be represented by the peak pressure value and the impulse. Combinations of pressure and impulse of various blast loading scenarios can be collected to draw a pressure-impulse (P-I) curve that corresponds to a level of damage of a blast-resistant structural component. The P-I curve is typically used for a preliminary design or assessment of blast resistance structural components. Generating a P-I curve for a given structural component and level of protection requires repeatedly running a single degree of freedom system (SDOF) model, which can be tedious for early design stages. Hence, a simplified approach (i.e., the normalization approach) was utilized to promptly generate the P-I curve for insulated precast concrete wall panels, which relies on shifting a control P-I curve using normalization factors. The generated P-I curves using the normalization approach are validated with the traditional SDOF approach curves; 95% of the examined insulated panel configurations have an error between +/- 7%. As a result of the reached low error percentages, a spreadsheet-design tool was developed using this approach. The tool can further enable rapid evaluation of the performance of insulated precast concrete panels under blast loading during the preliminary design phase.

Keywords:

Precast concrete;
 Insulated panels;
 Blast design;
 P-I curves;
 Design tool.

1 Introduction

Precast concrete wall panels can provide the necessary strength and durability with higher fabrication quality control and rapid erection. However, they possess a high thermal conductivity (ranging from 0.3 to 3.3 W/m·K) which is unsuitable for minimization of energy consumption [1]. To obtain energy savings benefits, an insulated layer, such as foam with low thermal conductivity (ranging from 0.0014 to 0.05 W/m·K), can be sandwiched between two layers of concrete [2]. This configuration system is commonly called insulated wall panels or sandwiched wall panels. Ties are used to connect the two layers of concrete and resist various loads that are generated during the lifting, shipping, erection, and final position. Ties are fabricated with various geometries, stiffness, and strength and developed with low thermal conductivity to prevent thermal bridging between the two layers of concrete. Based on the design of the ties, the flexural performance of the sandwiched panels can be classified into composite, non-composite, or partially composite. Insulated precast concrete panels are an excellent option for a blast-resistant structural component due to their energy efficiency and high mass, providing greater blast resistance. Their capability to provide good performance when subjected to blast loading was proven by Naito, Beacraft, et al. (2014) [3].

During the blast design stage for a structural element, a level of protection (LOP) that can range from a high level (i.e., the element with superficial damage) to a very low level (i.e., the element with heavy damage) is selected [4]. Positive reflected pressure and impulse, generated due to a blast event, are typically used to inspect the structural element's capability of satisfying the selected LOP. Positive reflected pressure is estimated as the maximum positive pressure on blast history. Positive reflected impulse corresponds to the area under the blast history curve of the positive phase. The term "reflected" here refers to the worst case of a fully reflected blast load where the surface is perpendicular to the direction of the shock wave propagation. The structural element can experience the same LOP for varied reflected pressure and impulse combinations. The single degree of freedom model (SDOF) can be used

to identify these combinations, which can then be combined to form a pressure-impulse (P-I) capacity. The P-I curves are frequently used in blast-resistant applications, such as assessing levels of damage for structural components, defining safe stand-off distances, and estimating acceptable human injury thresholds [5–7].

The P-I curves are currently utilized as a design tool for various architectural façade components, such as non-bearing walls. Obtaining the peak reflected pressure and impulse combinations requires repetitive runs for the SDOF model, which may not be feasible for preliminary design stages or during bidding phases. The author has assisted in a previous study [8] in developing a simplified blast design tool that can instantly generate the P-I curve for solid precast reinforced concrete wall panels and state if the element meets or does not meet the LOP. This study aims to expand the previously developed design tool by including the insulated precast concrete wall panels option.

2 Background

2.1 SDOF analysis

During an explosion event, a disturbance occurs in the surrounding atmospheric pressure. It can be characterized by a sudden increase in pressure above the atmospheric level followed by a rapid decay, in the order of milliseconds, until reaching the ambient pressure. This period is defined as the positive phase of the pressure history. A negative period with a lower magnitude pressure than the atmospheric level is then generated following the positive phase. The typical pressure history of an explosion event is shown in Fig. 1. The figure also shows an idealization for the pressure history typically used where the positive phase is simplified to a triangular shape and the negative phase is conservatively omitted. As a result of the dynamic nature of the blast loading, a numerical analysis may be used to provide the response history of the structural component. The analysis procedure typically considers idealizing the real structural component to an equivalent SDOF system, as shown in Fig. 2. The use of the equivalent SDOF system approach is also recommended by design manuals, such as the unified facilities criteria (UFC 3 340 02) [9] and the precast and prestressed concrete institute (PCI) design handbook [10] for blast-resistant design. The SDOF system consists of a mass-spring system related to the blast-loaded component. The dynamic response of the structural component at the mid-span for each time step during the blast loading history can be achieved by solving the equation of motion of the SDOF system (1). The K_{LM} factor is used to transform the real system subjected to blast loading into an equivalent SDOF system. For example, the K_{LM} factor for a simply supported beam subjected to a uniform distributed loading is 0.78 for the elastic range and 0.66 for the plastic range. It should be noted that damping possesses a minor effect in the first few oscillations of displacement history which are more concerning under blast loading and thus is commonly neglected in blast-resistant design. More details about the idealization of the blast-loaded component can be found in Biggs (1964) [11].

$$K_{LM} M y''(t) + R(y(t)) = P(t) \quad (1)$$

Where:

M – the lumped mass of the system,

K_{LM} – the load-mass transformation factor,

$R(y(t))$ – the resistance function of the component,

$y(t)$ – the mid-span displacement of the panel as a function of time,

t – time,

$P(t)$ – the blast pressure versus time history.

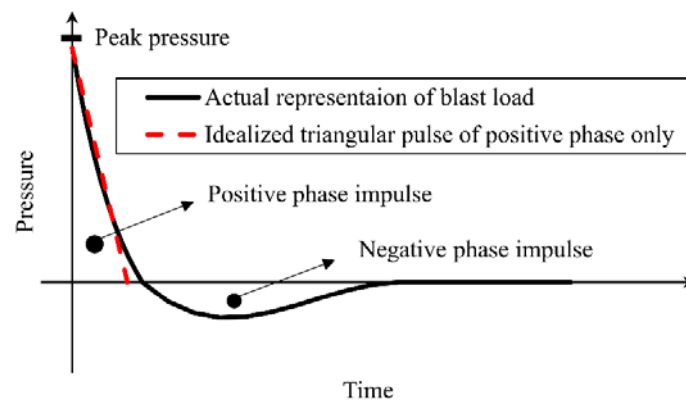


Fig. 1: Blast pressure time histories.

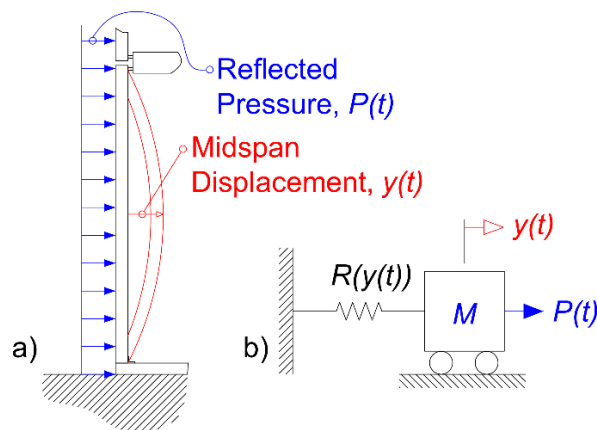


Fig. 2: Structural element subjected to explosive forces a) and simplified SDOF model b).

2.2 Resistance function of insulated panels

The resistance function considers an essential term in the equation of motion of the equivalent SDOF system. The resistance function defines the relation between the applied static load (resistance load) and the midspan deformation of the blast-loaded structural system. The resistance function can be idealized for most structural components, such as elastic and perfectly plastic ranges for simply supported boundary conditions or elastic, elasto-plastic, and plastic ranges for fixed-fixed boundary conditions. The number of ranges before reaching the plastic range is based on the type and number of supports in the structural component. The resistance function can be determined through conventional static methods that consider the inherent characteristics of the materials, compatibility, and balance of forces. Dynamic increase factor *DIF* is applied to the material strength to account for the high strain rate response due to blast loads.

The ultimate resistance of the structural element can be defined using the moment capacity and the span length. The moment capacity for insulated concrete panels can be calculated considering composite, non-composite, or partially composite action [2,5,7]. The composite moment capacity, M_c , is calculated by assuming a linear strain profile along the depth of the insulated panel (Fig. 3a). The non-composite moment capacity is defined by assuming independent resistance of the top and bottom concrete wythes to the applied loads, i.e., denoted as M_{nc_top} and M_{nc_bot} , respectively (Fig. 3b). The resistance amount is based on each wythe's relative flexural stiffness. The flexural resistance of the foam wythe is assumed to be negligible. An example of the flexural resistance function for an insulated reinforced concrete that possesses the same configurations except one considered as a composite section (solid black line) and the other as non-composite (red dashed line) is shown in Fig. 4. The partially composite response occurs at the region between the composite and non-composite resistances, as explained in [13]. The partially composite response is not within the scope of this study.

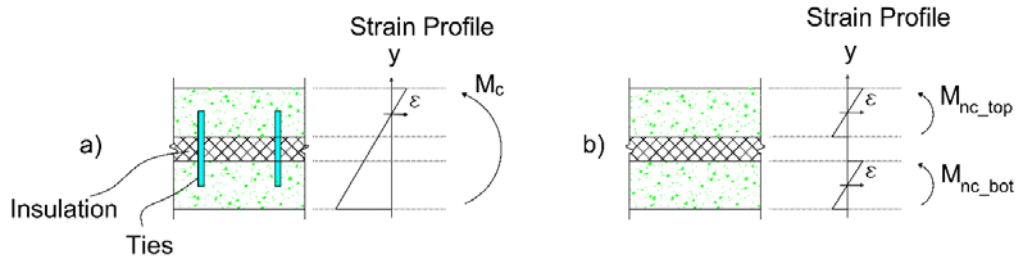


Fig. 3: Flexural behavior of a) composite section and b) non-composite section insulated concrete panels.

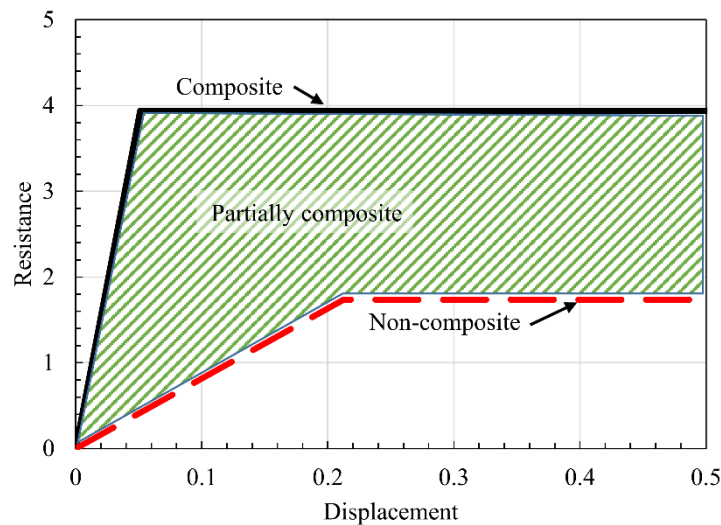


Fig. 4: An example of resistance function for composite, partially composite, and non-composite insulated concrete panels.

2.3 P-I curve

The P-I curve (or the iso-damage curve) is a diagram that shows the combination of positive peak pressure and positive impulse that will cause a specific level of damage, i.e., level of response limit. An earlier application for the P-I curve was used during World War II to assess the stand-off distances for explosive storages in the U.K. [6]. The P-I curve is also used to assess human injuries to blast loading, such as eardrums and lung damage [7]. The P-I curve is currently used in bidding phases to preliminary design building components, including proprietary window systems, curtain walls, and concrete wall systems. An example of a typical P-I curve is shown in Fig. 5. The P-I curve can be generated by performing numerous SDOF model runs until the selected level of damage is achieved based on the maximum displacement and commonly represented by ductility ratio or support rotations. Once the P-I curve is constructed, a wide range of potential blast hazards can be assessed where combinations of pressure and impulse fall to the left and below the curve meet the LOP; while those to the right and above the curve will not meet the LOP.

The P-I curve is bounded vertically and horizontally with two lines, i.e., called minimum impulse (I_0) and minimum pressure (P_0) asymptotes, which can be achieved analytically using equations (2) and (3), respectively. The P-I diagram encompasses three delineated sectors: impulsive, dynamic, and quasi-static, as visually presented in Fig. 5. These regions can be defined based on the relative relationship between the load function and the structural response.

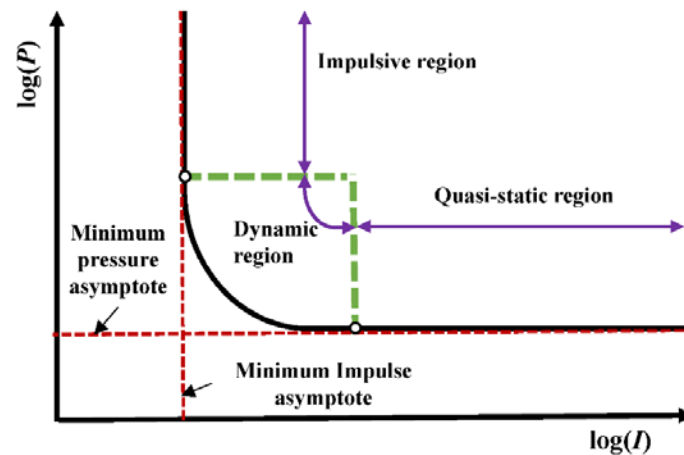


Fig. 5: Pressure-impulse curve.

$$I_0 = \sqrt{2 \times E \times K_{LM} \times M} \quad (2)$$

Where:

K_{LM} – the load-mass transformation factor,

E – the strain energy inherent in the resistance function of the element, explicitly referring to the enclosed area beneath the resistance function curve up to the deformation aligning with the specified LOP.

$$P_0 = \frac{E}{y_{Limit}} \quad (3)$$

Where:

y_{Limit} – the deformation aligning with the specified LOP.

2.4 Simplified approaches

Numerous iterations of SDOF analysis are required to generate a P-I curve for a selected response limit of a blast-resistant structural component, which can be arduous, especially during the preliminary design phases. As a result, recent research efforts have presented different simplified approaches to produce P-I diagrams for blast-loaded components. Li & Meng (2002a) and Li & Meng (2002b) [14,15] created a normalized P-I curve for elastic and elastic-plastic SDOF systems that work with different pulse loading forms. Fallah & Louca (2007) [16] used analytical formulae to estimate the P-I curves of idealized structural components. The formulae are based on an SDOF system with a bilinear resistance deflection curve exposed to various pulse loading forms. Using this approach, one point in the dynamic range must be found to construct the P-I curve. Shi et al. (2008) [17] developed a normalized P-I curve for reinforced concrete columns by deriving analytical formulae as a function of constitutive parameters. Dragos & Wu (2013) [18] offered an analytical methodology based on an empirical technique for developing a normalized curve for any pulse loading form and bilinear resistance function. Dragos et al. (2013) [19] generated a normalized P-I curve for simply supported, one-way, and ultra-high-performance concrete slabs using two derived formulas that are a function of member and sectional properties. Wang et al. (2013) [20] established an analytical equation to create P-I curves for a one-way reinforced concrete slab based on impulse and pressure asymptotes. Grisaro (2022) [21] derived a dimensionless P-I diagram for triangular blast load and elastic, elastic-plastic, and elastic-plastic with hardening systems. The study indicated qualitative judgment to compare the predicted and the numerically calculated P-I curve, while quantitative analysis may be needed for a more robust output of the P-I curve.

Alawad et al. (2019) [8] investigated two approaches for rapidly generating P-I curves for reinforced concrete precast solid wall panels: a normalization approach and a curve fitting method. The normalization approach involves shifting a given P-I curve of a control panel to construct the P-I curve for the wall panel of interest based on shifting factors corresponding to the pressure and impulse asymptotes ratio between the component of interest and the control component. The shifting factors can

be obtained using equation (4) for impulse (ψ_I) and equation (5) for pressure (ψ_P), where $P_{0,c}$, $I_{0,c}$ represent the control component asymptotes and P_0 , I_0 correspond to the asymptote of the component of interest. Equations (6) and (7) will then be used to form the P-I curve of the component of interest by shifting the vectors of the impulse and pressure of the control component via the ratio factors. The study compared the normalization approach P-I curve with the SDOF P-I curve for a wide range of one-way single-span solid wall panel configurations and linear and non-linear performance, where 95% of the examined cases possessed error percentages between +/- 6%. Due to the acceptable accuracy, the study suggested utilizing the normalization approach during the preliminary design phases. The study also developed a spreadsheet tool further to facilitate practitioners' generation of the P-I curves.

$$\psi_I = \frac{I_0}{I_{0,c}} \quad (4)$$

$$\psi_P = \frac{P_0}{P_{0,c}} \quad (5)$$

$$I = \psi_I \times I_c \quad (6)$$

$$P = \psi_P \times P_c \quad (7)$$

Where:

ψ_I – impulse shifting factor,

ψ_P – Pressure shifting factor,

$P_{0,c}$, $I_{0,c}$ – the control component asymptotes,

P_0 , I_0 – the asymptote of the component of interest,

P_c , I_c – the control component vectors.

As a result of the limited range set of components in the aforementioned studies, additional studies may be required to assess simplified approaches when used to evaluate the performance of insulated concrete wall panel applications. Hence, this study aims to examine the normalization approach when used for insulated precast wall panel configurations. The outcome of this study will allow including the insulated panel's option in the previously developed spreadsheet tool, which offers a broad selection of various types of reinforced concrete panels for practitioners during the early design phases. This study focus on one-way flexural performance that insures unidirectional failure modes while bidirectional deformation analysis, such as in [22,23], is not consider in this study.

3 Methodology

A range of non-prestressed insulated concrete wall panel components was selected to achieve the purpose of the study. This range includes composite and non-composite flexural behavior, two foam thicknesses, six areas of steel, five span lengths, five compressive strengths, three boundary conditions, and three response limits, corresponding to 5400 insulated wall panel design configurations. Table 1 summarizes the selected parameters in the study. Three steps are performed to achieve the aim of the study. Generating the P-I curves for the selected range of non-prestressed insulated panel components via the SDOF model will be first performed. The second step is generating the P-I curves via the normalization approach for the selected range. The last step is comparing the P-I curves of the normalization approach with the SDOF P-I curves.

The SDOF P-I curve is generated by running the SDOF model repeatedly by altering the reflected pressure and impulse. The reflected pressures and impulses that cause the maximum displacement to match the selected level of protection response are recorded (i.e., at least 15 points recorded) to generate the SDOF P-I curve. To generate the P-I curves of the normalization approach for the selected range, a control component is selected, and its SDOF P-I curve is obtained, given in Table 2. The control component asymptotes, $P_{0,c}$ and $I_{0,c}$, are 26.34 kPa (3.82 psi) and 520.56 kPa-ms (75.50 psi-ms), respectively. The configuration of the selected control component is shown in Fig. 6. The P-I curve of the normalization approach can then be generated by shifting the P-I curve of the control component via the shifting factors using equations (4) and (5).

A quantitative comparison with the SDOF P-I curves is then established to ensure the accuracy of the P-I curves generated via the normalization approach. The error between each point on the

normalized curve and the SDOF curve is evaluated using equation (8), where subscripts labeled “SDOF” and “NM” represent the values for the SDOF and normalization curves, respectively. The comparison is made by initially dividing the P-I curve into three regions, i.e., impulsive, dynamic, and quasi-static regions, as shown in Fig. 5. On the impulsive regions, the pressure point on the normalized curve is interpolated to equate the point on the SDOF curve. The pressure term in equation (8) will vanish, and the impulse points will be directly compared. Similar consideration is performed for the points in the quasi-static region, yet, a direct comparison is carried out for the pressure points. A radial comparison that accounts for both pressure and impulse variations is performed on the points within the dynamic region. More details on the error calculation procedure can be found in Alawad et al. (2019) [8]. The comparison is accomplished for all insulated precast concrete wall panels and response limits selected in the study.

Table 1: Selected parameters for the study. Note: 1 ksi = 6895 kPa, 1ft =12 in = 304.8 mm.

Boundary conditions	Simple-simple, simple-fixed and fixed-fixed
Response limits, deg.	1, 2 and 5
Type of flexural behavior of insulated panels	Composite and non-composite
Panel thickness, mm (in) (exterior-foam-interior)	76.2-50.8-76.2 (3-2-3) and 76.2-76.2-76.2 (3-3-3)
Bar sizes #, SI (U.S.)	10 (3), 13 (4), 16 (5), 19 (6), 22 (7), and 25 (8)
Span lengths, m (ft)	2.44 (8), 3.66 (12), 4.57 (15), 6.10 (20) and 9.14 (30)
Compressive strength, MPa (ksi)	27.58 (4), 34.47 (5), 41.37 (6), 48.26 (7) and 55.16 (8)

Table 2: Impulse and pressure values for the control component. Note: 1 psi = 6.895 kPa.

Control component	
I_c , [kPa-ms]	P_c , [kPa]
609.52	3447.50
612.97	1529.79
610.21	1019.01
597.11	452.17
594.35	301.24
612.28	133.63
650.20	89.01
749.49	59.30
1002.81	43.30
1164.57	39.51
1516.07	35.58
2291.97	32.13
3465.01	30.13
4260.42	29.44
6440.96	28.41
9737.53	27.79
22255.68	27.10
27364.60	26.96

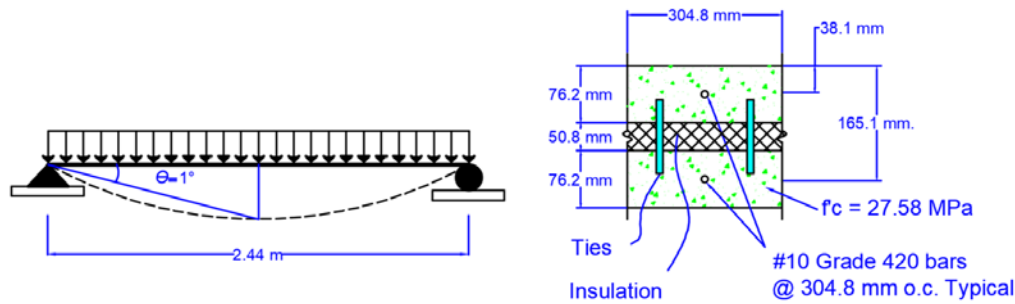


Fig. 6: Details of the control component. Note: 1 ksi = 6895 kPa, 1ft =12 in = 304.8 mm.

$$Error (\%) = \sqrt{\left(\frac{I_{SDOF}-I_{NM}}{I_{SDOF}}\right)^2 + \left(\frac{P_{SDOF}-P_{NM}}{P_{SDOF}}\right)^2} \times 100 \quad (8)$$

Where:

I_{NM}, P_{NM} – the values for the normalization curve,

I_{SDOF}, P_{SDOF} – the values for the SDOF curve.

4 Results and discussion

This section shows and discusses the implementation of the normalization method into generating the P-I curve for insulated precast concrete wall panels. It first illustrates an example of the development of the normalization P-I curve for an insulated precast wall panel element. Then, the section discusses the quantitative comparison between the normalization and the SDOF P-I curves for the selected range of the insulated precast panels in the study. Finally, the section demonstrates the implementation of the normalization approach into a spreadsheet tool to further facilitate the rapid evaluation of the blast resistance of insulated precast panels during the early design stages and bidding process of a project.

4.1 An example of developing the P-I curve via the normalization approach

The SDOF and normalization P-I curves are generated for the selected set wall panels, boundary conditions, and level of protection. An example of generating the P-I curve of a selected component of interest (see Fig. 7 for details) is explained hereafter for a fully composite insulated sandwich wall panel with simply supported boundary conditions. The panel is 15 ft (4572 mm) tall. The panel has a 3 in (76.2 mm) exterior wythe of concrete, a 3 in (76.2 mm) insulation layer of foam, and a 3 in (76.2 mm) interior wythe of concrete. #7 (#22) rebars are located at the thickness center of the exterior and interior concrete wythes each. The tension reinforcement located at the interior wythe of concrete is at a depth of 7.5 in (190.5 mm) on center from the extreme compression fiber. The concrete has a compressive strength of 7 ksi (48.26 MPa), and grade 60 (420) steel reinforcement is used. The concrete density is 150 pcf (2403 kg/m³). The static increase factor for the steel reinforcement is 1.10. The DIFs for steel and concrete are 1.17 and 1.19, respectively. It is important to note that a unit foot (304.8 mm) width will be analyzed, and reinforcement at the exterior wythe will be neglected. The following steps are utilized to obtain the normalization P-I curve for the selected component of interest:

Step 1. Known variables of the control component:

Boundary conditions:	Simply supported
Type of panel:	Full-composite
Panel thickness (exterior-foam-interior):	3-2-3 in (76.2-50.8-76.2 mm)
Area of #3 (#10) bar:	$A_{sc} = 0.11 \text{ in}^2 (70.97 \text{ mm}^2)$
Span length:	$L_c = 8 \text{ ft} (2.44 \text{ m})$
Depth of reinforcement:	$d_c = 6.5 \text{ in} (165.1 \text{ mm})$
Concrete compressive strength:	$f'_c = 4 \text{ ksi} (27.58 \text{ MPa})$
Total thickness of concrete wythes:	$h_c = 6 \text{ in} (152.4 \text{ mm})$
Concrete unit weight:	$\gamma_c = 150 \text{ pcf} (2403 \text{ kg/m}^3)$
Minimum impulse asymptote:	$I_{0,c} = 75.5 \text{ psi-ms} (520.55 \text{ kPa-ms})$
Minimum pressure asymptote:	$P_{0,c} = 3.82 \text{ psi} (26.34 \text{ kPa})$
Impulse and pressure for response limit 1°:	See Table 2

Step 2. Given parameters of the targeted component:

Boundary conditions:	Simply supported
Type of panel:	Full-composite
Panel thickness (exterior-foam-interior):	3-3-3 in (76.2-76.2-76.2 mm)
Area of #7 bar:	$AS_T = 0.6 \text{ in}^2$ (387.1 mm ²)
Span length:	$L_T = 15 \text{ ft}$ (4.57 m)
Depth of reinforcement:	$d_T = 7.5 \text{ in}$ (190.5 mm)
Concrete compressive strength:	$fc'_T = 7 \text{ ksi}$ (48.26 MPa)
Total thickness of concrete wythes:	$h_T = 6 \text{ in}$ (152.4 mm)
Concrete unit weight:	$\gamma = 150 \text{ pcf}$ (2403 kg/m ³)
Concrete elastic modulus:	$E_c = 33 \times 150^{1.5} \times \sqrt{7000} = 5072.2 \text{ ksi}$ (34971.6 MPa)
Dynamic steel tensile strength:	$f_{dy_T} = 1.17 \times (1.10 \times 60) = 77.22 \text{ ksi}$ (532.4 MPa)
Dynamic concrete strength:	$f_{dc_T} = 1.19 \times 7 = 8.33 \text{ ksi}$ (57.4 MPa)

Step 3. Find the dynamic moment capacity of the targeted component:

Dynamic moment capacity:

$$M_{du} = AS_T \times f_{dy_T} \times \left(d - 0.5 \times \frac{AS_T \times f_{dy_T}}{0.85 \times f_{dc_T} \times b} \right)$$

$$M_{du} = 0.6 \times 77.22 \times \left(7.5 - 0.5 \times \frac{0.6 \times 77.22}{0.85 \times 8.33 \times 12} \right)$$

$$= 334.86 \text{ kip} \cdot \text{in} \text{ (37.83 kN} \cdot \text{m)}$$

Step 4. Compute elastic stiffness and ultimate resistance at mid-span of the targeted component:

Average moment of inertia:

$$I_{av} = \frac{I_g + I_{cr}}{2} = \frac{702 + 134.78}{2}$$

$$= 418.39 \text{ in}^4 \text{ (1.74} \times 10^8 \text{ mm}^4)$$

Elastic stiffness:

$$k = \frac{384 \times E_c \times I_{av}}{5 \times L_T^4 \times b}$$

$$k = \frac{384 \times 5072200 \times 418.39}{5 \times 180^4 \times 12} = 12.94 \frac{\text{psi}}{\text{in}} \text{ (3.51} \frac{\text{kPa}}{\text{mm}})$$

Ultimate resistance:

$$r_u = \frac{8 \times M_{du}}{L_T^2 \times b}$$

$$r_u = \frac{8 \times 334860}{180^2 \times 12} = 6.89 \text{ psi} \text{ (47.51 kPa)}$$

Step 5. Compute the impulse and pressure asymptotes of the targeted component:

Elastic and plastic load mass factor:

$$K_{LM} = 0.78 \text{ (elastic), } K_{LM} = 0.66 \text{ (plastic)}$$

Mass:

$$M = \frac{h_T \times \gamma}{g} = \frac{6 \times 150 \times 1000^2}{386 \times 12^3}$$

$$= 1348 \text{ psi} \cdot \frac{\text{ms}^2}{\text{in}} \text{ (375.68 kPa} \cdot \frac{\text{ms}^2}{\text{mm}})$$

Mid-span displacement at 1°:

$$y_{limit} = \tan(\theta) \times L_T \times 0.5 = 1.57 \text{ in} \text{ (39.88 mm) (larger than } y_e)$$

Strain energy:

$$E = 0.5 \times r_u \times y_e + r_u \times (y_{limit} - y_e)$$

$$= 8.99 \frac{\text{lb}}{\text{in}} \text{ (1.57} \frac{\text{kN}}{\text{m}})$$

Impulse asymptote:

$$I_0 = \sqrt{2 \times E \times K_{LM} \times M}$$

$$= \sqrt{2 \times 8.99 \times 0.66 \times 1348}$$

$$= 126.47 \text{ psi} \cdot \text{ms} \text{ (871.98 kPa)}$$

Pressure asymptote:

$$P_0 = E/y_{limit} = 8.99/1.57 = 5.72 \text{ psi} \text{ (39.44 kPa)}$$

Step 6. Compute impulse and pressure normalization factors:

Impulse normalization factor:

$$\psi_I = I_0/I_{0,c} = 126.47/75.5 = 1.675$$

Pressure normalization factor:

$$\psi_P = P_0/P_{0,c} = 5.72/3.82 = 1.498$$

Step 7. Develop the impulse and pressure curve for the targeted component, as shown in Table 3 and Fig. 8:

Impulse:

$$I = \psi_I \times I_c \quad (6)$$

Pressure:

$$P = \psi_P \times P_c \quad (7)$$

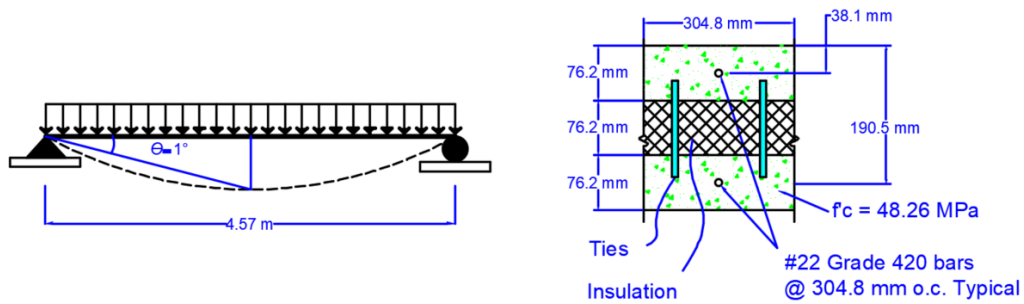


Fig. 7: Details of the selected component of interest. Note: 1 ksi = 6895 kPa, 1ft =12 in = 304.8 mm.

Table 3: Impulse and pressure values for the component of interest. Note: 1 psi = 6.895 kPa.

Component of interest	
$I = 1.675 \times I_c$ [kPa-ms] (6)	$P = 1.498 \times P_c$ [kPa] (7)
1021.01	5164.36
1026.80	2291.62
1022.18	1526.48
1000.19	677.36
995.57	451.21
1025.63	200.23
1089.13	133.35
1255.44	88.88
1679.76	64.88
1950.73	59.16
2539.50	53.37
3839.27	48.06
5804.21	45.09
7136.60	44.06
10789.16	42.61
16311.09	41.65
37280.02	40.54
45837.89	40.40

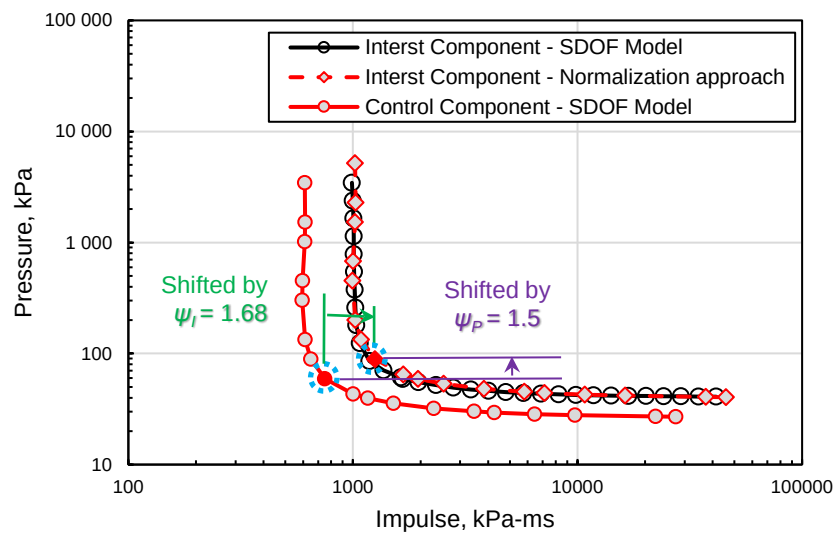


Fig. 8: Generated P-I curves using SDOF analysis and normalization approach.

Note: 1 psi = 6.895 kPa.

4.2 Normalization and SDOF results comparison

The previous section showed an example of developing the P-I curve via the normalization approach. Generating the P-I curve of the component of interest is achieved by shifting the vectors of the P-I curve of the control component using the shifting factors calculated using equations (6) and (7) for impulse and pressure, respectively, as shown in Table 3 and Fig. 8. Fig. 8 also shows the SDOF P-I curve of the component of interest where the P-I curve of the normalization approach appears to match it well qualitatively. To ensure the robustness of the approach, a quantitative comparison is performed between each point on the normalized curve and the SDOF curve for all insulated panels and response limits in the study using equation (8). The total error for each component is then determined using a root mean square calculation. The total error for the examined components in the study is plotted using the probability density function (PDF), as shown in Fig. 9. Approximately 95% of the examined cases have error percentages between $\pm 7\%$. Hence, the normalization approach reached an acceptable accuracy as a preliminary design tool to evaluate non-prestressed insulated precast concrete panels when subjected to far-field blast loading. It should be noted that the variation between the simplified and traditional SDOF P-I diagrams mainly occurred in the dynamic region. The steepness concavity of the control P-I curve varies from other examined cases. Li and Meng (2002) [15] showed that the concavity steepness may vary based on the stiffness and whether the maximum deformation falls within or beyond the elastic zone.

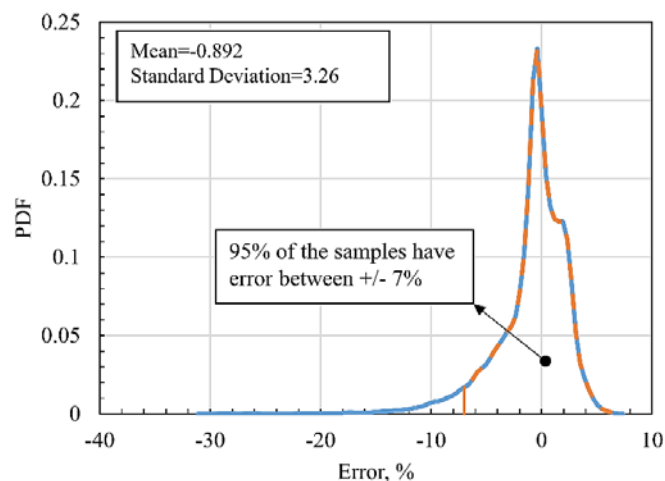


Fig. 9: Probability density function of errors for the normalization approach.

4.3 Simplified blast tool

As explained earlier, this study aims to upgrade the spreadsheet-based tool provided by Alawad et al. (2019) [8]. The option of non-prestressed insulated concrete panels is included in the spreadsheet-based tool as a result of the acceptable reached accuracy. The tool will further facilitate the implementation of the normalization approach by conventional engineering practitioners, such as design consultants, construction contractors, and precast concrete suppliers, during the preliminary design stages and the bidding process. The tool user can rapidly evaluate the component status by inserting the blast pressure and impulse demand and selecting the desired response limit. The user then can include the constitutive properties of the component of interest, after which the tool can determine whether the component has met the desired response limit (i.e., level of protection). If not, the user can easily modify the constitutive properties of the component (e.g., increasing the area of steel) until the level of protection for the component is satisfied. The updated simplified tool is provided at [PrecastBlastTool-1-2.xlsx \(sharepoint.com\)](#).

5 Conclusion

Typical generation for the P-I curve using the SDOF analysis requires several iterations, which can be tedious for practitioners, especially during the early design stages. Therefore, the present study used a simplified approach (the normalization approach) to rapidly develop the P-I curve for non-prestressed, non-load-bearing, insulated precast concrete wall panels. A comparison between the P-I curves generated via the normalization approach and the traditional SDOF approach was conducted for a wide range of insulated concrete panels. The comparison revealed that 95% of the examined panels reached low error percentages (i.e., between $\pm 7\%$). As a result of the acceptable accuracy for most of the examined cases, the option of insulated panels was included in the previously developed version of the spreadsheet-based tool further to ease the use of the normalization approach by specialists. The tool allows the user to determine whether the panel of interest has met the level of protection for a given blast pressure and impulse, as well as the constitutive properties of the panel. Few examined cases had higher error percentages, which may be attributed to the degree of concavity steepness of the dynamic region curve from control P-I curves. Hence, this approach is only suited for preliminary design stages and is limited to far-field blast loads. More structural configurations, such as prestressed concrete and steel beams or panels, and levels of protection can be included in the tool's future versions, which allows users to examine wider options.

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