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COMPARISION OF BLAST PERFORMANCE OF CORRUGATED AND FLAT STEEL PLATES

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Abstract

Blast-resistant modular steel (BRMS) buildings are prefabricated structures designed to provide cost-effective protection against blast loads. They serve as critical shelters for personnel working near hazardous material handling facilities, high-pressure processes, and designated blast zones in the mining, petrochemical, and military industries. BRMS buildings typically incorporate steel plate blast-resistant walls made from either flat steel plates or corrugated steel plates with a trapezoidal cross-section. These wall panels are the key structural elements, as they withstand the highest blast forces on surfaces directly exposed to an explosion. This study evaluates the blast performance of flat and corrugated wall plates with varying aspect ratios using blast pressure-impulse (P-I) curves. A series of wall panels with different aspect ratios are analyzed through explicit dynamic blast simulations to account for large deflections. The results show that plate aspect ratio has minimal influence on the blast performance of corrugated plates. However, flat plates exhibit significant sensitivity to aspect ratio variations in their blast response. Notably, with optimal design, flat plates can achieve blast resistance comparable to that of corrugated plates. These findings offer valuable insights for optimizing BRMS wall panel design to enhance their explosion resilience.

Keywords: Corrugated Plate, Large Plate Deflection, Pressure Impulse Curves, Plate Aspect Ratio.

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1 INTRODUCTION

Due to growing terror threat and accidental explosions, blast performance of structures is becoming an important structural design consideration for not only military structures but also for structures at petrochemical industry and industrial plants to ensure safety and protection of personal. Blast loads, which are typically ignored in the design of such structures, have effects including but not limited to structural damage, personal casualties, and social and economic impacts. Especially, the terror attacks on the Oklahoma City Federal Building and World Trade Center buildings, which resulted in total building collapse and massive loss of life, have attracted the attention of many researchers to improve blast resistance of structures [1,2,3]. The primary design objective for structures subjected to blast loading is to ensure structural integrity and thereby preventing or limiting loss of life [2,4,5]. Unless the structure is very critical, it is not economical and practical to ensure that the deformations and structural damage remain within elastic limits for an unlikely blast event. Therefore, deformations occurring in structural components under blast loads are allowed to be beyond their linear elastic limits (i.e., plastic deformation) to minimize the cost. Hence, blast damage is typically measured in terms of deformations instead of internal loads (e.g., shear, moment) as done in seismic design.

To minimize cost, prefabricated blast resistant modular steel (BRMS) structures have recently become very common as economic solutions especially in petrochemical industry as control rooms, office buildings, and living quarters [5]. Figure 1 shows a typical three-module blast-resistant modular steel-framed structure during and after installation. The BRMS structures are recognized as an economical and practical solution to minimize blast effects and valuable assets for protection of personnel involved in activities located near potential explosion sites [5,6]. These structures are widely used as control rooms, office buildings, and living quarters in areas with a high risk of explosion, fire, or danger from toxic materials in petrochemical industry, and temporary living shelters in military areas.

Typically, BRMS building wall panels are either corrugated (trapezoidal cross-section) or flat steel plate sections while the floor and roof are covered with flat steel plates. The wall panels are generally the most critical structural elements for blast loading because the blast load is the largest on the surfaces directly facing the blast. Despite the ease of connecting flat steel wall panels to the frame elements, corrugated steel wall panels, which have good ductility capacity, are also preferred for the walls. In this study, the blast performance of flat and corrugated wall plates with varying aspect ratios is computed and compared using blast pressure-impulse (P-I) curves. The evaluation of blast performance is performed using explicit dynamic analysis to account for plate large deflections and effects of membrane action.

Figure 1: Typical blast-resistant modular building.

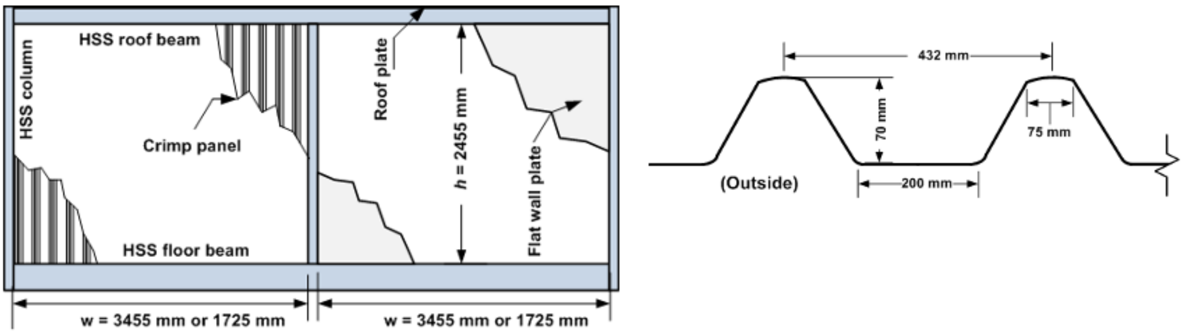
2 PROTOTYPE FLAT AND CORRUGATED PLATES

The prototype wall configurations considered in this study are summarized in Table 1. For both flat and corrugated plates, the plate height is set at 3455 mm, corresponding to height of a typical BRMS buildings shown in Figure 2a. Two plate width cases are considered: 3455 mm, which results in a width-to-height ratio of 1.0, and 1725 mm, corresponding to an aspect ratio of 0.5. The thickness of all plates is taken as 5 mm, which is typical for BRMS steel wall panels. The corrugated plate section profile, which is shown in Figure 2b, has a total depth of approximately 70 mm and a peak-to-peak distance of 432 mm. The plates are welded along all four edges on both the exterior and interior surfaces using fillet welds to resist rebound blast forces induced by the blast loading.

The same material properties are assumed for both flat and corrugated steel plates. The modulus of elasticity is 210,000 MPa, and Poisson's ratio is taken as 0.3. The yield strength is specified as 338 MPa, while the ultimate tensile strength is 348 MPa, corresponding to a strain of 0.3. Additionally, the slope of the strain hardening region is taken as 860 MPa. These parameters are selected to ensure a realistic representation of typical steel material behavior under blast loading conditions.

Plate ID	Plate Shape	Plate height (*h*)	Plate width (*w*)	Aspect ratio
FPL1	Flat	3455 mm	3455 mm	1.0
FPL05			1725 mm	0.5
CPL1	corrugated	3455 mm	3455 mm	1.0
CPL05			1725 mm	0.5

Table 1: Plate properties.



(a) Flat and corrugated plate sample wall section (b) Corrugated plate profile

Figure 2: Wall plate (a) geometry and (b) corrugated plate profile.

3 PLATE FINITE ELEMENT MODEL

The three-dimensional finite element (FE) models of the plates are developed using the general-purpose finite element software ABAQUS 6.20 [6]. This software is selected for its computational efficiency in modeling nonlinear behavior, including both material and geometric nonlinearities, which are critical for accurately capturing the response of thin plates where membrane action plays a significant role. The computational models, as shown in Figure 3, are meshed with a nominal element size of 25 mm for all plates. This mesh size is chosen to ensure an accurate representation of the corrugated plate geometry and is validated through a mesh sensitivity analysis. The S4R shell element, a four-node quadrilateral element with reduced integration and large-strain formulation, is utilized for all plate models. This element is a general-purpose conventional shell element that accounts for transverse shear deformation, making it suitable for thin-walled structures.

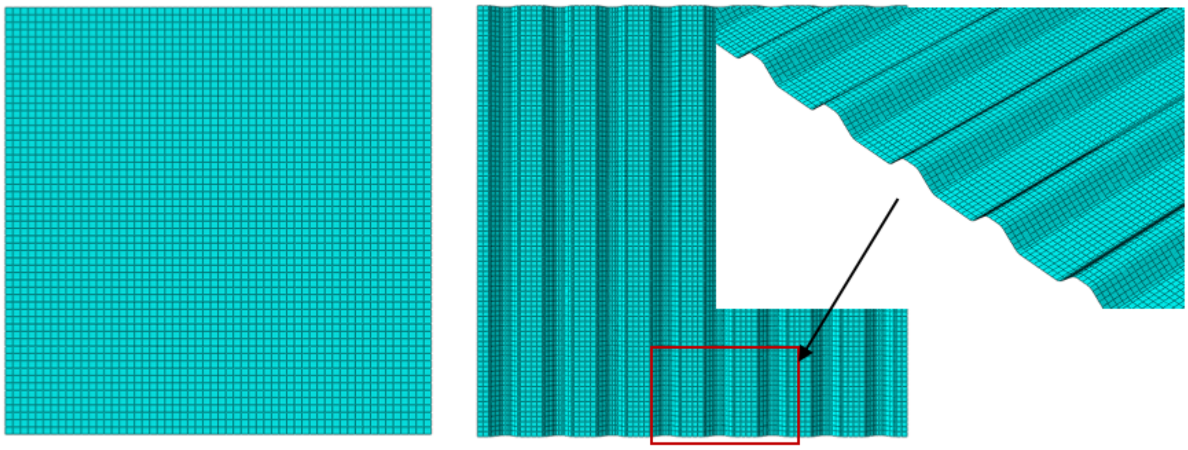


Figure 3: plate finite element model and mesh

The boundary conditions assume that all edges of the plates are fixed in all three displacement and rotation degrees of freedom. This assumption is consistent with common fabrication practices, where both flat and corrugated plates are welded on both sides to the building beam and column framing members. The blast loading is applied as pressure loading as shown in Figure 4.

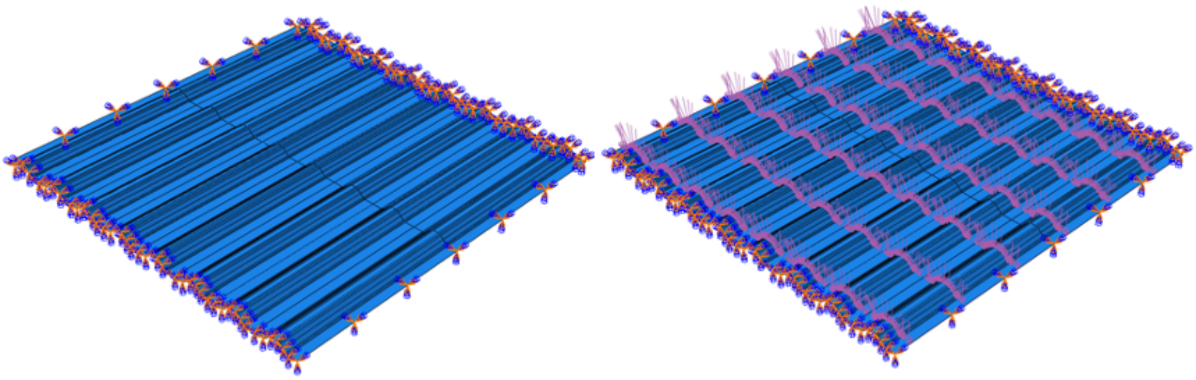


Figure 4: Plate boundary condition and application of blast pressure.

Two types of analyses are performed. The first is a static pressure loading analysis, in which pressure is applied using a smooth amplitude function. This analysis is conducted to evaluate the relationship between the applied load and the plate center deflection, as well as to examine how this behavior changes under large deflections. Due to the nonlinear nature of the problem, the analysis is performed using dynamic explicit solver with mass scaling to enhance computational efficiency while accurately capturing large deformation effects. Applying an explicit dynamic procedure to quasi-static problems helps address computational challenges associated with large deformations and local buckling. Mass scaling is incorporated to improve computational efficiency. To ensure that the analysis remains quasi-static, the kinetic energy of the model is maintained below 2% of the total internal energy, as recommended for quasi-static simulations [6]. This constraint ensures that dynamic effects remain negligible in the static loading analysis. The second analysis is dynamic explicit simulation without mass scaling, which is used for blast loading conditions.

All analyses performed incorporate both geometric and material nonlinearities. Geometric nonlinearity plays a significant role in the response of the plates due to the large deformations they undergo, where the primary load resistance occurs through membrane action that depends on the deformed configuration. The inclusion of geometric nonlinearity is also essential for capturing phenomena such as snap-through behavior in corrugated plates and local buckling under pressure loading and large displacements.

4 BLAST LOADS AND PRESSURE-IMPULSE CURVES

During an explosion, energy is rapidly released, creating shock waves that propagate through the atmosphere. This transforms the explosive material into a high-temperature, high-pressure gas that expands outward, generating a powerful blast wave. The wave's leading edge experiences a sudden pressure rise, known as incident overpressure (P_{so}). When it strikes a structure, it reflects and amplifies, producing a higher reflected pressure (P_r) as shown in Figure 5. The blast wave consists of a positive phase, where overpressure decreases back to ambient levels, followed by a weaker, longer-lasting negative phase. Because the negative phase has minimal structural impact, blast-resistant designs primarily consider the positive phase as shown in Figure 5 [4,7].

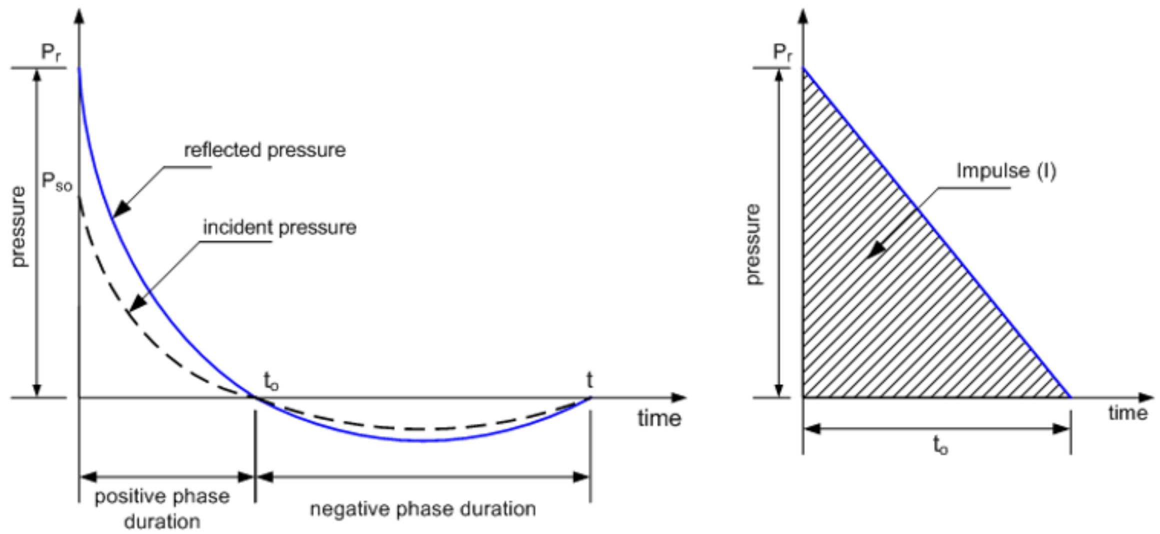


Figure 5: Typical blast pressure-time curves and impulse.

The magnitude and distribution of blast loads on a structure depend on several factors, including the type and quantity of the explosive material, the location of the detonation relative to the structure, and the interaction of the pressure wave with the ground or nearby surfaces. One of the most effective methods for designing structural elements to resist blast loads is the use of Pressure-Impulse (P-I) diagrams, where impulse is area under pressure-time curve as shown in Figure 5. These diagrams consist of iso-damage curves that represent different combinations of reflected blast pressure and impulse, each corresponding to a specific level of structural response. The P-I curves are particularly useful in the early stages of design, allowing engineers to approximate the dynamic response of structural components without requiring detailed numerical simulations. This approach significantly reduces the need for complex dynamic analysis while ensuring a cost-effective and efficient design process.

According to the American Society of Civil Engineers (ASCE) guidelines [4], the displacement response of steel plates subjected to blast loading is classified into three distinct levels based on support hinge rotation limits. A low response level corresponds to a hinge rotation limit of 3 degrees, a medium response level to 6 degrees, and a high response level to 12 degrees. Hinge rotation is quantitatively defined as the peak deflection of the component normalized by the distance from the support. The maximum center displacements corresponding to each response level are presented in Table 2.

Plate ID	Low response		Medium response		High response	
	θ	Δ (mm)	θ	Δ (mm)	θ	Δ (mm)
FP1	3	91	6	182	12	367
FP05		45		91		184
CPL1 CPL05	3	91	6	182	12	367

Note: Both crimp panels are working as one-way plate and therefore support rotation is calculated along plate height (*h*)

Table 2: Plates blast response levels and corresponding maximum center deflection.

The blast performance of the plates is assessed using computed P-I diagrams at the high-damage response level (hinge rotation of 12 degrees) rather than under specific blast loads. This methodology ensures a consistent basis for comparing performance across plates with varying geometries and aspect ratios at large displacement levels. To construct the P-I diagrams, each plate is analyzed under two scenarios: either by holding the blast pressure constant while increasing the load duration or by maintaining a fixed load duration while progressively increasing the pressure until the target displacement is reached.

5 RESULTS AND DISCUSSIONS

The static deflection response of the plates, as shown in Figure 6, reveals notable differences between the flat plates (FPL1 and FPL05) and the corrugated plates (CPL1 and CPL05). The two corrugated plates have almost identical pressure-deflection response and therefore only one of them is shown. At small deflections where the membrane action is not significant, the stiffness of corrugated plates is larger than those of flat plates. This is due to corrugated plate cross-section having larger moment of inertia due to corrugated profile. However, at large deflection, the stiffness of both FL1 and FL05 are larger than that of the corrugated plates due to increased plate bending stiffness because of large out-of-plane deflection and corresponding membrane action. The stiffness of corrugated plates does not increase as much as flat plate due to corrugated section local buckling as shown in Figure 7. The corrugated plates response indicate that the plates resist loads in a one-way action, even for the square plate (CPL1), and does not develop a significant membrane action in other direction.

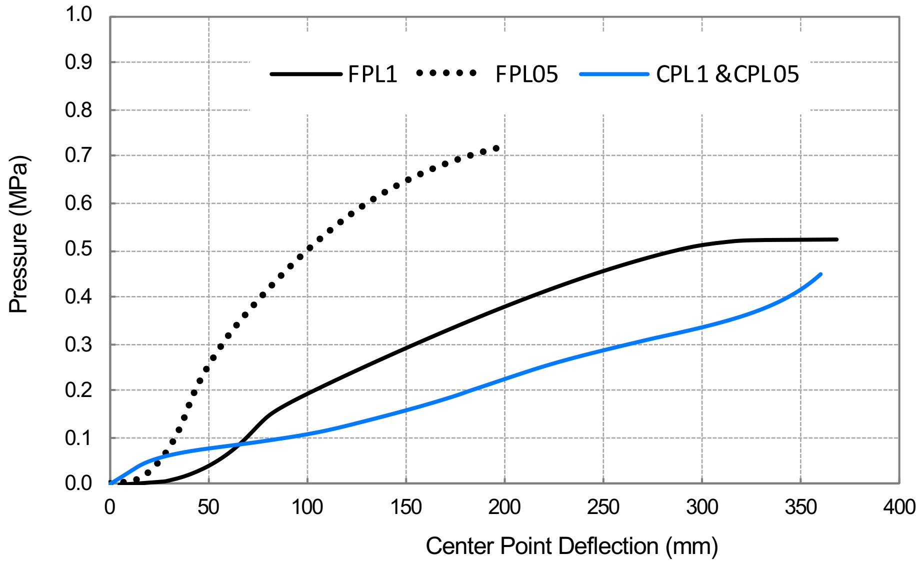


Figure 6: Plates pressure-deflection curves with nonlinear quasi-static analysis.

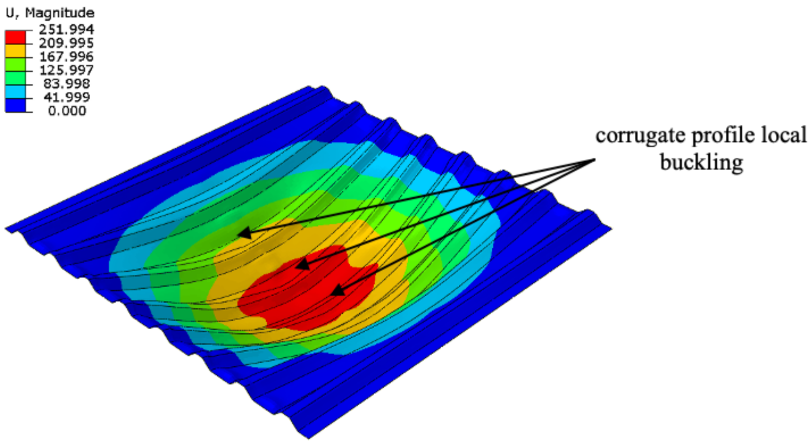


Figure 7: Corrugated cross-section local buckling at large deflection.

The computed P-I curves for the high-damage response level, given in Figure 8, provide a comprehensive comparison of the blast performance of flat and corrugated plates. The results indicate that the corrugated plates (CPL1 and CPL05) exhibit very similar behavior, which is consistent with their static response. This similarity arises from the corrugated profile, which enforces a one-way load-resisting mechanism under blast loading for both plates. In the impulse-sensitive region, where pressure is high, the corrugated plates demonstrate a resistance that is higher than that of FPL1 but lower than FPL05. On the other hand, in the pressure-sensitive region, where impulse is high, the corrugated plates reach the response level at much smaller pressure levels compared to both flat plates.

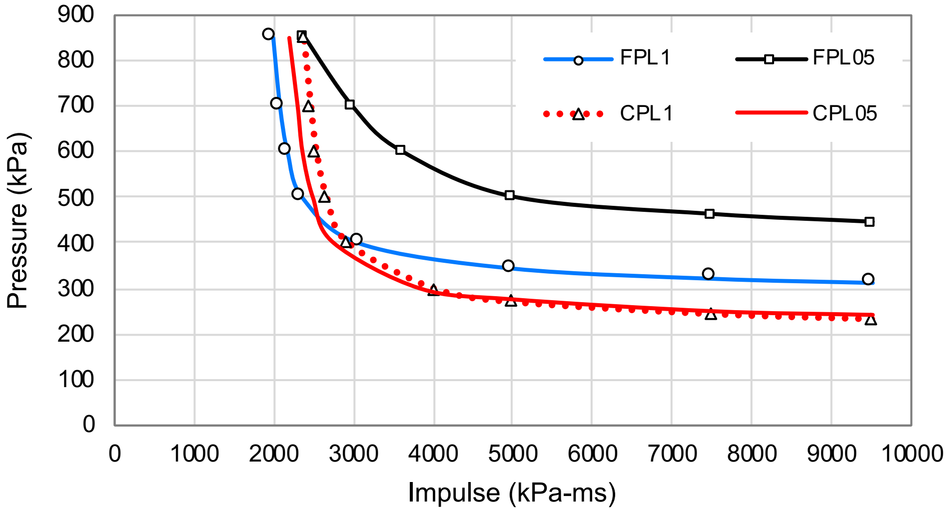


Figure 8: Plates pressure-impulse (P-I) curves for high damage response level.

A key observation is that the aspect ratio of the corrugated plates has minimal influence on their blast response or P-I curve. This highlights the dominance of the corrugate profile in dictating structural behavior under blast loads. On the other hand, plate aspect ratio significantly affects the P-I curves for the flat plates. The square flat plate (FPL1) exhibits the best overall response in all P-I curve regions. This indicates that for flat plates, aspect ratio plays a crucial role in determining blast resistance. This effect is particularly pronounced in the pressure-sensitive region, where impulse values are large while pressure remains relatively low. These findings emphasize the importance of selecting plate geometry based on the specific nature of blast loading, with flat plates providing superior performance under high-impulse conditions, while corrugated plates offer a more uniform response in impulse sensitive region where pressure is high, and impulse is small.

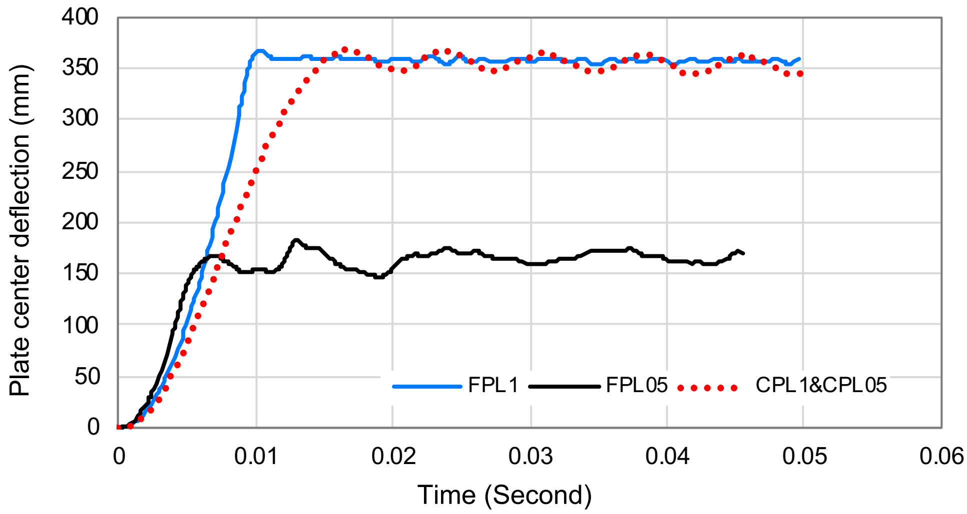


Figure 9: Plates deflection time-history curves.

The time-history responses of the plates center deflection under blast loading are given in Figure 9. The results indicate that the overall initial stiffness of both flat plates is larger than that of the corrugated plates. Once the blast pressure drops to the ambient level, all plates continue to vibrate around a shifted equilibrium position, reflecting significant plastic deformation and permanent displacement. Flat plate FPL1 and corrugated plates CPL1 and CPL05 show plastic deformations approaching the deflection limit of 367 mm. These large plastic deformations are expected, as the plate response level is set to high-damage level. Notably, the steady-state vibration of FPL1 and FPL05 after the blast pressure returns to ambient conditions appears more irregular and random. In contrast, the corrugated plates exhibit a more harmonic vibration pattern, suggesting that they experience less structural damage and retain better post-blast stability compared to the flat plates.

6 CONCLUSIONS

This study evaluates the blast performance of flat and corrugated steel plates with varying aspect ratios in prefabricated blast-resistant modular structures. The key findings are as follows:

- Flat plates exhibit higher overall initial stiffness, but their response is highly sensitive to plate aspect ratio.
- Square flat plates perform best overall under blast loads for both pressure and impulse sensitive loading cases.
- Flat plates blast resistance can be comparable to corrugated plates, but their response is significantly affected by plate aspect ratio.
- Corrugated plates provide a more uniform and predictable response, largely independent of plate aspect ratio since their one-way load resistance mechanism limits significant membrane action in other directions due to corrugated profile.

These findings highlight the importance of plate geometry selection in optimizing structural resilience for high-risk environments.

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