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An Optimized Stiffened Sandwich Panel for Impact-Protective Doors

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ABSTRACT:

Protective steel doors are widely used in buildings due to their high resistance against the impact loads. However, its heavy weight has been always considered as a major drawback for these doors. In this paper, a new optimized stiffened impact-protective steel door incorporating sandwich panel with aluminum foam core (OSSA) is examined. This door consists of two face sheets, main and secondary stiffeners, and aluminum foam as the inner core. In order to optimize the door, at first the rigidity and weight functions of the stiffened steel door were extracted. Then an optimal door weighing 42% less than the primary door was obtained. Due to the high energy absorption capacity of the combined foam core and stiffened steel door structure, the use of aluminum foam core in the optimized steel door was proposed. By doing numerical analysis, and depending on the thickness of the face sheet of OSSA, 20 to 32% reduction in the maximum displacement was observed. The results also showed that, with 67% increase in the peak overpressure, OSSA has kept almost the same maximum displacement as that of the steel door without an aluminum foam. In other words, by using aluminum foam core in the optimized stiffened door, the door will resist 67% more impact load.

KEYWORDS:

Stiffened structure, Impact-protective steel door, Sandwich panel, Metal foam.

1. Introduction

Accidental or intentional impact load must be considered in the analysis and design of buildings. Designing fully impact-protective structure is not a realistic and economical option. However, structural engineers intend to make new and existing buildings more resistant against the effects of impact loads. Therefore, many studies have investigated the effect and behavior of impact loads (Ngo et al. 2007; Guzas and Earls, 2010; Jankowiak et al. 2014; Abbasi and Nia, 2020; Palta et al. 2018; Shrivastava et al. 2020; Xu Wl, et al. 2019).

Today, it is important to design impact-protective structures to reduce financial and human life losses. An efficient method in the dissipation of the energy of impact, is the use of impact-protective doors. These doors reduce casualties and increase the possibility of relief. Various types of impact-protective doors were designed for different applications (Anderson M, Dover D, 2003; Koh C, et al. 2003). A common type of these impact-protective doors is steel plates with stiffeners (Veeredhi and Rao 2003). Stiffeners increase the stiffness and energy dissipation, they are commonly used to produce impact-protective lightweight structures such as buildings, military shelters, impact-protective doors (Zheng et al. 2016; Tavakoli and Kiakojouri 2014; Jen and Tai 2010). Goel, et al. (2011) studied the dynamic response of stiffened plates and investigated the effects of stiffener configuration. They found out that the stiffened plate with cross stiffener configuration had the highest response reduction. One of the most common types of impact loads is the blast load, which can cause serious damages to the structure and its occupants. Nurick et al. (1995, 1996) and Rudrapatna et al. (2000) investigated possible failure modes of a stiffened plate under blast load numerically and experimentally. Louca et al. (1998)

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compared dynamic responses of stiffened and unstiffened plates by numerical methods. To prevent local failure, secondary stiffeners, thinner and denser stiffeners, were employed to form structures named hierarchical (Wang et al. 2015; Wang et.al 2017; Sun et al. 2016). Fan et al. (2008) proposed anisogrid hierarchical stiffened structures to create light structures and prevent local and overall buckling. Sui et al. (2016) also developed isogrid hierarchical panels. Veeredhi et al. (2015) studied the impact-protective door made of steel plate with stiffeners. The results showed that increasing the size of the stiffeners reduces the maximum displacement. Meng et al. (2016) designed and tested a hierarchical stiffened door made of Sheet Molding Compound (SMC) with main and secondary stiffeners. The results showed that these doors are light and stiff enough to resist blast loads. In another study, Zhang et al. (2018, a) presented the dynamic response of a hierarchical panel consisting of main and secondary stiffeners. Due to the high pressure in some places and the cracks created in the door designed by Meng et al. (2016), by changing the location, number, and shape of the stiffeners, Zhang et al. (2018, b) designed and tested another door, including the main and secondary stiffeners of SMC materials without FRP. The results showed a 65% reduction in maximum displacement.

Another method to increase the impact energy dissipation is the use of sandwich panels. These panels are lightweight structures that can significantly absorb the energy of impact loads (Xie et al. 2014; Yurddaskal and Baba 2016; Rashad and Yang, 2018). A sandwich panel with metal foam consists of a metal foam core located between two metal face sheets. The metal foams have a good performance against impact load due to the low density and high strength to weight ratio (Liang et al. 2017; Darvizeh and Davy 2015; Liang et.al 2019; Zhang et al. 2013). Among metal foams, aluminum foams are widely used (Cai et al. 2020; Li et al. 2017; Chen et al. 2019; Santosa et al. 2017). Santosa et al. (2017) analyzed sandwich panels with an aluminum foam core and steel and aluminum face sheets against the blast load. The results showed an effective reduction in the maximum displacement. Langdon et al. (2010) performed experiments to investigate the behavior of sandwich panels with an aluminum foam core with different face sheet thicknesses under blast load. The results showed that by using aluminum foam core, the thickness of the face sheet could be reduced. Lui et al. (2013) conducted experiments to study the response of sandwich panels with aluminum foam cores under blast load. The results showed that the aluminum foam core absorbs the blast energy to a large extent.

Today, well known factories produce impact-protective doors. These doors are usually made of steel, concrete, or a combination of steel and concrete. They are easy to install and have a relatively reasonable price, but they are heavy. This paper proposes a new optimized stiffened impact-protective steel door incorporating a sandwich panel with aluminum foam core (OSSA). This study consists two parts: In the first part, the stiffened impact-protective steel door is investigated and the dimensions of the main stiffeners and consequently the steel door are optimized. The second part involves the use of aluminum foam as a sandwich panel in the door structure, optimized in the first part.

2. Optimized stiffened impact-protective steel door

Steel, has several advantages such as fast installation, easy construction, high tensile and compressive strength, high ductility and durability, recyclability (up to 85%) and easy strengthening, is a favorite material in the construction industry. A major disadvantage of steel is that it loses its strength and softens at high temperatures. However, fire-resistant coatings and sprays can improve its performance under such conditions. In this study therefore, impact-protective doors made of steel components are examined.

A hierarchical stiffening system made of Sheet Molding Compound (SMC) material was suggested by Zhang et al. (2018, b), where two types of main and secondary stiffeners were employed to enhance flexural rigidity of an impact-protective door. Such a system is shown in Fig.1.a, where the main stiffeners include five transverse and three longitudinal stiffeners. Secondary stiffeners are thinner but denser, and are designed to prevent the local failure of the face sheet.

(a) (b)

Fig. 1. (a) A typical hierarchical orthogrid-stiffened impact-protective door, (b) simplified blast wave curve

Typically, to investigate the damage of the structure, it is necessary to set limit values for some representative measures of the structure's response. Suitable criteria for structures such as impact-protective doors are the maximum rotation of supports denoted by θ and ductility ratio denoted by μ, which is defined as the ratio of maximum displacement (x_m) to elastic displacement equivalent to the yield strength (x_E) shown in Eq. (1).

$$\mu=\frac{x_m}{x_E} \tag{1}$$

According to Unified Facilities Criteria (UFC) (2008), for the level of performance with moderate safety, the upper limit of the ductility ratio is taken to be 10, and the rotation angle is limited to 6 degrees. Therefore, these two limit values are used to determine whether or not the impact-protective door is within the specified level of performance. In addition to the mentioned criteria, it is always desirable to design a lightweight impact-protective door. To achieve minimum weight, the dimensions of the door components must be determined so that constraints on the criteria of selective level of performance are met (the value of θ must be less than 6 degrees and the value of μ must be less than 10).

In this study, due to practical considerations, the thickness of the face sheet is considered to be a fixed value of 5mm. Moreover, due to a minor contribution of the secondary stiffeners in the total weight of the door, only the height and thickness of the main stiffeners are considered as the main parameters of the optimization process.

To control the performance criteria, the values of μ and θ should be determined by analyzing the door under impact load using Ls-Dyna, and compared with the upper-limit values. To limit the number of analyses, the following procedure is adopted: For a given weight of the door, the height and thickness of the main stiffeners are determined by maximizing the flexural rigidity of the stiffened panel. Then, the door with these stiffeners is fully modelled and analyzed in Ls-Dyna (c.f. section 2.2), and thus, the values of μ and θ are calculated. We proceed then by explaining the flexural rigidity of stiffened panel and provide the details of the modeling in Ls-Dyna.

2.1. Flexural rigidity of stiffened panel

The flexural rigidity of the stiffened panel can be obtained from equivalent theory (Zhang et al. 2018, c) which has been verified using finite element simulation results (Zhang et al. 2018, a). The basic principle of the equivalent theory requires that the stiffened panel have equal bending and extensional rigidity to the equivalent homogeneous panel. As shown in Fig. 2, the equivalence process consists of two steps. The first step is to smear the hierarchical stiffened panel to a stiffened panel and the second step is to smear the stiffened panel to a homogenous panel. 0

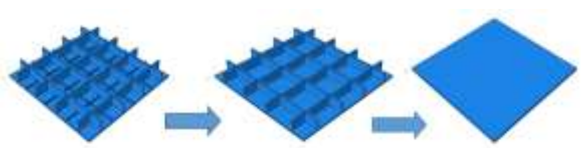

Fig. 2. Schematic of the equivalence process in the two step

Fig. 3. shows the considered hierarchical stiffened panel and the corresponding two sections. In this model, the thickness of the face sheet is h_p and the height and thickness of the secondary stiffeners are h_s and b_s, respectively. The height of the main stiffeners is h_m. To simplify the analyses, the thickness of the main longitudinal and transverse main stiffeners is considered the same and denoted by b_m. The distance between two adjacent longitudinal stiffeners is denoted by d_x and the distance between two adjacent transverse stiffeners is denoted by d_y. The distance from the natural plane to the mid-plane of the panel, including longitudinal stiffeners, is shown by z_{nx}.

In contrast, the distance from the natural plane to the mid-plane of the panel, including transverse stiffeners, is shown by z_{ny}. By applying the two steps of equivalence theory, the flexural rigidity (D_x and D_y) of stiffened panel is obtained as Eq. (2), where E is the Young's modulus and ν is the Poisson's ratio of steel.

$$\begin{Bmatrix} D_x \\ D_y \end{Bmatrix}=\frac{E\,h_p^3}{12(1-\nu^2)}+\frac{E\,h_p}{(1-\nu^2)}\begin{Bmatrix} z_{ny0}^2+(1+\alpha)z_{ny}^2 \\ z_{nx0}^2+(1+\beta)z_{nx}^2 \end{Bmatrix}+ E\begin{Bmatrix} (I_{y0}+I_y)/d_y \\ (I_{x0}+I_x)/d_x \end{Bmatrix}$$

Where:

$$\alpha=\frac{b_s h_s}{d_y h_p}, \quad \beta=\frac{b_s h_s}{d_x h_p}$$

$$z_{nx0}=\frac{b_s h_s(h_s+h_p)}{2(b_s h_s+d_x h_p)}, \quad z_{ny0}=\frac{b_s h_s(h_s+h_p)}{2(b_s h_s+d_y h_p)}$$

$$z_{nx}=\frac{b_m h_m\,(h_m+h_p)}{2\,[\,b_m h_m+(1+\beta)d_x h_p]}, \quad z_{ny}=\frac{b_m h_m\,(h_m+h_p)}{2\,[\,b_m h_m+(1+\alpha)d_y h_p]}$$

$$I_{x0}=\frac{b_s h_s^3}{12}+b_s h_s\left(\frac{h_s}{2}+\frac{h_p}{2}-z_{nx0}\right)^2$$

$$I_{y0}=\frac{b_s h_s^3}{12}+b_s h_s\left(\frac{h_s}{2}+\frac{h_p}{2}-z_{ny0}\right)^2 \tag{2}$$

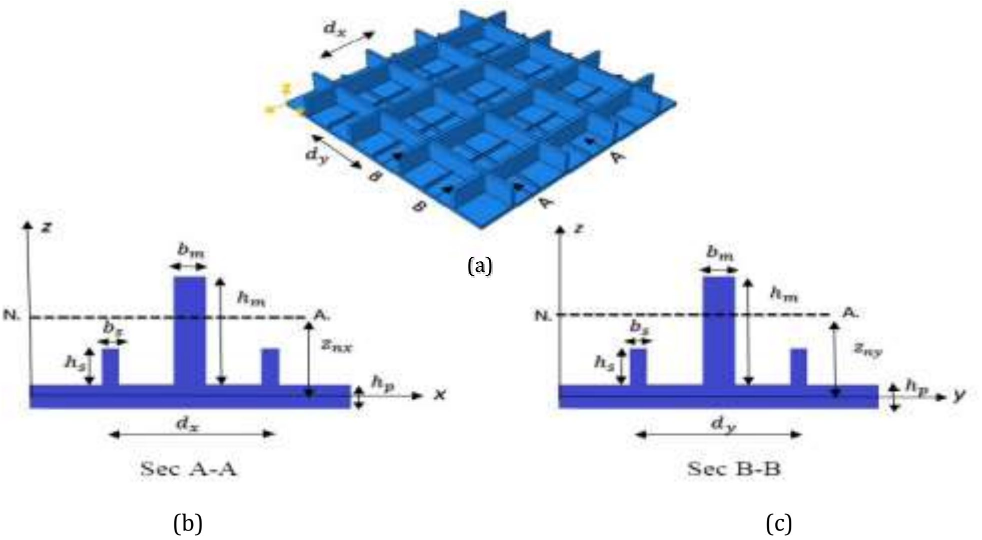

Fig. 3. (a) details of the hierarchical stiffened panel, (b) section A-A, (c) section B-B

2.2. Modeling sof the impact-protective door in Ls-Dyna

Ls-Dyna is employed to model the impact-protective steel door. Due to the symmetry, a quarter of the door is modelled. MAT-PLASTIC–KINEMATIC with solid elements is adopted to model the behavior of steel. This model, according to researches, is in good agreement with laboratory results (Abedini et al. 2021; Stawinski et al. 2017).

The dimension of the mesh for hexahedron elements is 1mm. To reduce the computation time and prevent the occurrence of hourglass energy, the full integral algorithm is employed. The steel used in this study is ST52, with properties given in Table 1. According to study done by Zhang et al. (2018, b), to model the frame as rigid steel supports, the MAT-RIGID model is used, and all displacements and rotations are constrained. In addition, AUTOMATIC-SURFACE-TO-SURFACE contact is considered between the door and the frame. As shown in Fig.4, the door is simply supported on two longitudinal sides.

Like the SMC door of Zhang et al. (2018, b), the height of the door is 1760mm, and its width is 860mm. The main stiffeners have 15mm thickness and 80mm height. Secondary stiffeners have a thickness of 3mm and a height of 15mm. The stiffeners are placed on a 5mm thick bottom face sheet. The width and the thickness of the frame are 85mm. As shown in Fig. 5, the load is applied uniformly on the face sheet of the door the load is applied uniformly on the face sheet of the door, according to the impact load curve shown in Fig. 1b. We use the same method for modeling the SMC door as presented by Zhang et al. (2018, b) to validate this model. The details are given in Appendix A, in which the results indicate a close correlation with that of the experimental tests.

Table 1. Properties of the applied steel

Density	Young’s modulus	Yield stress	Plastic modulus	Poisson’s ratio
7850 (Kg/m^3)	210 GPa	400 MPa	1 GPa	0.3

2.3. Optimization

The weight function is obtained from the dimensions of the door’s components (including the frame) and the density of steel. Since the secondary stiffeners make only 2% of the total weight of the door, only the height and thickness of the main stiffeners are selected as parameters affecting the optimization process. Therefore, the weight function (in kg) is written only in terms of these two parameters and by applying numerical values of the other parameters, the weight function is obtained as follows:

$$W=91.912+0.5864\, h_m+0.0636\, h_m b_m \quad (3)$$

For a given weight of the door, the optimization process at first requires to maximize the flexural rigidity of stiffened panel. To this end, Eq. (3) helps to write b_m as a function of h_m for a given W. Now, D_x and D_y in Eq. (2) are given as functions of h_m and thus we can maximize a function such as $D=(D_x+D_y)/2$ to obtain the optimized value of h_m. By placing the optimal value of h_m in Eq. (3), we can obtain the corresponding value of b_m.

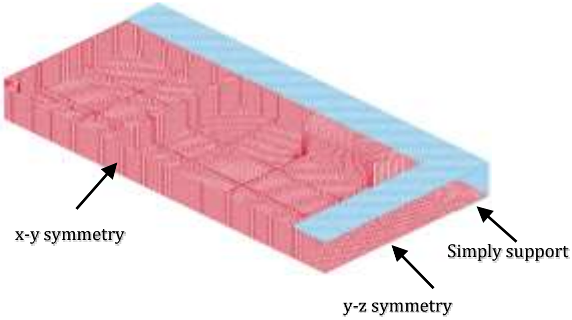

Fig. 4. A quarter model of the stiffened steel door modeled in Ls-Dyna

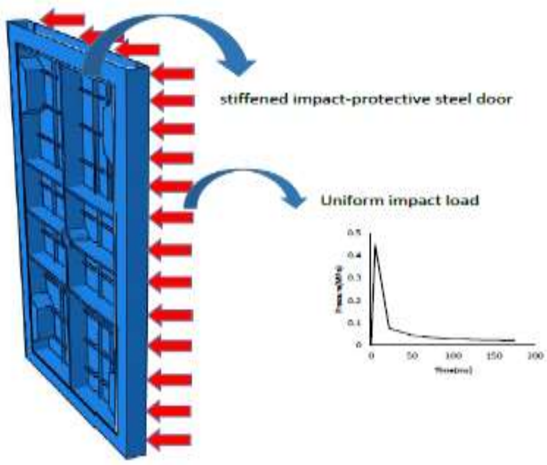

Fig. 5. Impact loading applied to the door

This process is performed for various values of W to determine the corresponding values of h_m and b_m. The results are summarized in Table 2 for selected values of W in the range of 115kg<W<160 kg. The optimization process continues with modeling these doors in Ls-Dyna, as explained in section 2.2. The values of ductility ratio and rotation angle are calculated and compared with their upper limits related to the selected performance level, summarized in Table 2.

The results presented in Table 2 show that the amount of rotation angle is greater than 6° for W≤115kg. Moreover, for doors with the weight of 160, 145, 140, 135, 130 and 125Kg, the ductility ratio is larger than the defined limit, i.e., 10. However, the value of this criterion for doors of 155, 150,120 and 115kg weight is less than this limit. Thus, the door with a weight of 120kg, including the main stiffeners with a height of 31mm and a thickness of 5mm, which is the minimum weight in the permissible limit of both ductility ratio and rotation criteria for the level of performance with moderate safety, can be introduced as an optimized door. As a result, with a 42% reduction, the weight of the stiffened steel door is reduced from the initial value of 206kg (related to the impact-protective door presented by Zhang et al (2018b), if we replace the SMC material with steel) to the optimal value of 120kg. Notably, the maximum displacement for this optimal door is obtained as 25.8mm

Table 2. Summary of the results of optimized steel door analysis

Weight(kg)	h_m (mm)	b_m (mm)	μ	θ°	μ<10	$\theta < 6^{\circ}$
160	79	4.3	12.6	2.1	×	✓
155	72	4.6	9.8	3.1	✓	✓
150	65	5	5.53	3.86	✓	✓
145	61	4.5	11.6	4.2	×	✓
140	55	4.5	11.9	4.6	×	✓
135	50	4.5	12.97	4.8	×	✓
130	43	4.8	11.4	4.98	×	✓
125	37	4.8	10.27	5.2	×	✓
120	31	5	7.77	5.36	✓	✓
115	24	5.5	6.73	6.1	✓	×

It is instructive to study the sensitivity of results to variations of h_m and b_m in the optimal door. First, a set of doors containing the main stiffener with h_m=31mm and variable thicknesses from 4.5 to 5.5 mm (with an increase of 0.1mm in each step) are considered, and the ductility ratio and rotation angle values for these doors are calculated. The results are shown in Fig. 6.

As Fig. 6.a shows, for a constant value of height, increasing the thickness of the main stiffener decreases the value of the ductility ratio and for b_m<5mm, the ductility ratio is more sensitive to the changes of b_m. Fig. 6.b also shows that the thickness alterations for constant height of the main stiffener do not have a significant effect on the rotation angle.

A set of doors containing the main stiffener with b_m=5mm and variable height from 40 to 80mm (with an increase of 10mm in each step) is considered next. The values of ductility ratio and rotation angle for these doors are calculated. The results are shown in Fig. 7. As Fig. 7.a shows, for a constant value of thickness, increasing the height of the main stiffener decreases the value of the ductility ratio, and for h_m>60mm, the ductility ratio is more sensitive to changes of h_m. Fig. 7.b also shows that the rotation angle decreases almost linearly with increasing height.

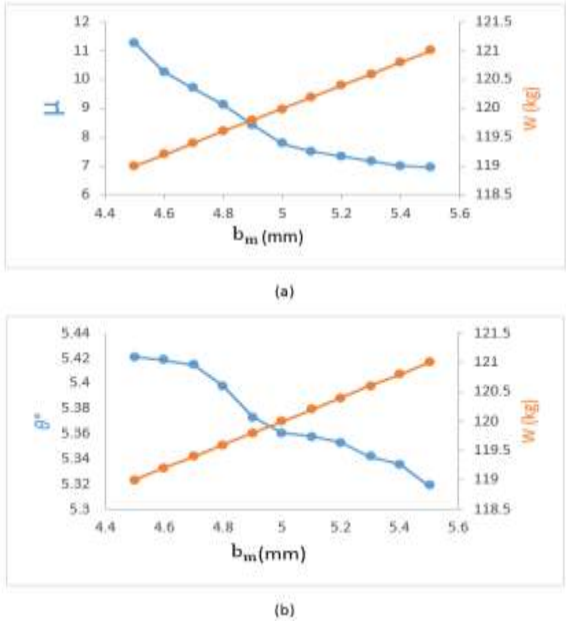

Fig. 6. Effects of the changes in main stiffener's thickness on: (a) ductility ratio, (b) angle of rotation (with h_m=31mm)

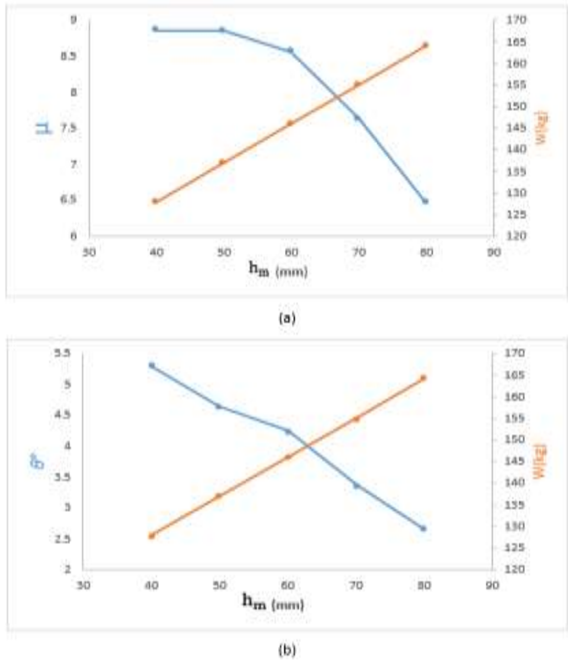

Fig. 7. Effects of the changes in main stiffener's height on: (a) ductility ratio, (b) angle of rotation (with b_m=5mm)

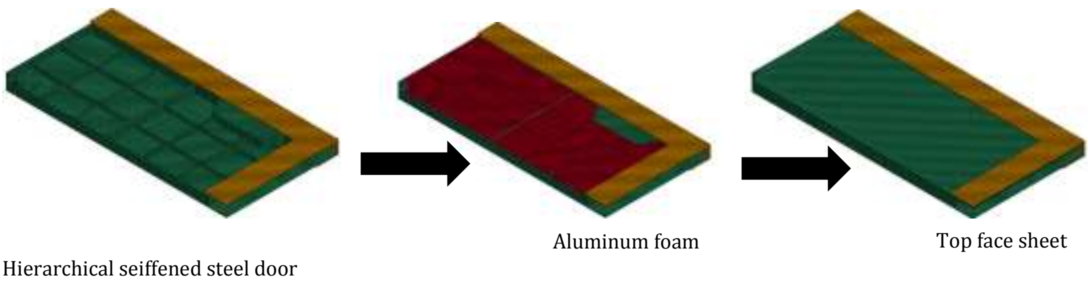

Fig. 8. The construction steps of OSSA for a quarter of the model

3. Stiffened impact-protective steel door incorporating sandwich panel with aluminum foam core

To absorb more energy and enhance the efficiency of the stiffened impact-protective steel door, the effect of the combination of stiffeners and aluminum foam is investigated. The mechanism of behavior of aluminum foam core sandwich panels is that the face sheet which is in front of the impact load begins to deform. While the foam core becomes compressed, it rapidly transfers the momentum to the back face sheet. The excellent compressibility of the foam core facilitates energy dissipation during impact loading (Ganchao et al. 2019).

To make the stiffened impact-protective steel door incorporating sandwich panel with the aluminum foam core (OSSA), the foam is applied inside the steel door which was optimized in section 2. In this regard, the space between the stiffeners is covered with aluminum foam. According to the concept of sandwich panel, the second face sheet must be used on the foam. This sheet is made of steel with 5mm thickness, similar to the main face sheet. However, various thicknesses of this face sheet will be examined. The construction steps of OSSA are shown in Fig. 8.

3.1. Modeling in Ls-Dyna

Details of the modeling of the stiffened impact-protective door were given in section 2-1. Here, we provide further details regarding the foam core that is added to the door structure.

There exist several material models in Ls-Dyna to model the aluminum foam, including CRUSHABLE-FOAM, HONEYCOMB, and DESHPANDE-FLECK-FOAM. In this study, CRUSHABLE FOAM model is used due to its proper adaptation with laboratory results (A.G.Hansssen et al. 2001). ALPORAS type aluminum foam is selected and its stress-strain diagram is shown in Fig.9 based on laboratory results (Jianhu Shen et al. 2010). The specifications used in the modeling are listed in Table 3 (Wei Li et al. 2014).

The CONTACT-AUTOMATIC-SURFACE-TO-SURFACE-TIEBREAK model is used to model the contact between the face sheets and the foam core (Wei Li et al. 2014). The tiebreak failure criterion at this contact is defined as:

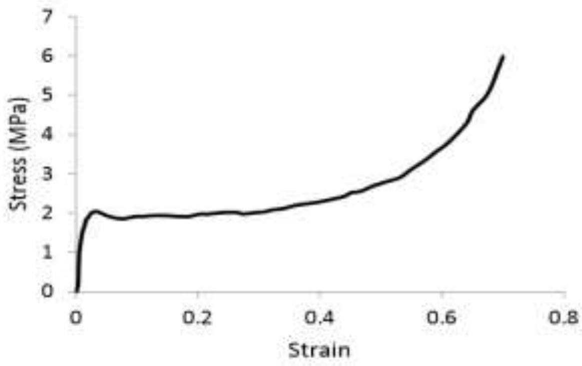

Fig. 9. Stress-strain diagram of ALPORAS aluminum foam (Al+1.5%Ca+1.5%Ti)

Table 3. Specifications of ALPORAS aluminum foam

Density	Young's modulus	Poisson's ratio	Tensile curve Cutoff	Rate sensitivity via damping coefficient
230 (Kg/m^3)	1.1GPa	0.33	1.6MPa	0.1

$$\left(\frac{|\sigma_n|}{NFLS}\right)^2 + \left(\frac{|\sigma_s|}{SFLS}\right)^2 \geq 1 \quad (4)$$

Where, σ_n is the normal stress and σ_s is the shear stress. In addition, NFLS is the normal failure stress, and SFLS is the shear failure stress, which are considered as 12MPa and 2.47MPa, respectively (Wei Li et al. 2014). In this contact model, it is important to consider the orientation of elements and parts in contact.

The CONTACT-AUTOMATIC-SINGLE-SURFACE model is used to model the contact between the face sheets and the foam core to penetration. The static and dynamic friction coefficients of the contact are 0.28 and 0.2, respectively (Wei Li et al. 2014). The CONTACT-INTERIOR model is used to prevent foam self-penetration, which occurs under high pressure and may lead to negative volume.

3.2. Results

Fig. 10. shows the stress and displacement distribution of the protective steel door with the aluminum foam core under the dynamic impact load shown in Fig. 1.b. The result show that the maximum stress occurs at the main stiffeners, and the maximum displacement occurs at the central point of the door.

3.2.1. Increase in load

To further evaluate the OSSA, the peak overpressure of the impact load, according to FEMA428 (2003) is elevated from 0.45MPa to a maximum value of 0.75MPa, and the door is analyzed with the same other conditions. As shown in Fig. 11, the maximum displacement is 25.7mm. Since the maximum displacement of the optimized steel door without foam with an overpressure of 0.45MPa is 25.8mm, it is observed that if the aluminum foam is used, with 67% increase in peak overpressure, the maximum displacement remains almost unchanged.

3.2.2. Decreasing the weight of OSSA

The dimensions of the main stiffeners of the steel door were optimized in Section 2. In this section, in order to reduce the weight of the OSSA, the effect of reducing the thickness of the second face sheet of the sandwich panel located on the foam is examined. OSSA, including optimized steel door introduced in section 2 and aluminum foam with a second face sheet with different thicknesses, is analyzed in Ls-Dyna.

Furthermore, the values of the ductility ratio in the steel part and the rotation angle are calculated and the results are summarized in Table 4. As Table 4 indicates, after reducing the thickness of the second face sheet to 1mm, the obtained OSSA, weighing 135kg, shows lower values of ductility ratio and rotation angle than the optimal steel door, and has a better performance. Also, the results show that the use of foam in OSSA, depending on the thickness of the face sheet, reduces the value of the ductility ratio by 26-33% and the rotation angle by 17-30%.

For a better comparison, the time variation of maximum displacement of the OSSA with 5mm and 1mm thickness of the second face sheet and the optimized steel door without foam (presented in section 2) are shown in Fig. 12.

As shown in Fig. 12, the OSSA with 5mm thickness of the second face sheet has a maximum displacement of 17.5mm, and the OSSA with 1mm thickness has a maximum displacement of 20.8mm while the optimized steel door without foam has a maximum displacement of 25.8mm.

Therefore, OSSA with a 5mm thick second face sheet has 32%, and OSSA with a 1mm thick second face has 20% less maximum displacement than the optimized steel door without foam. Thus, it is observed that the use of aluminum foam as a sandwich panel has significantly reduced the maximum displacement, which enhances the impact-protective door's efficiency. Furthermore, foam can act as a sound and heat insulator as well.

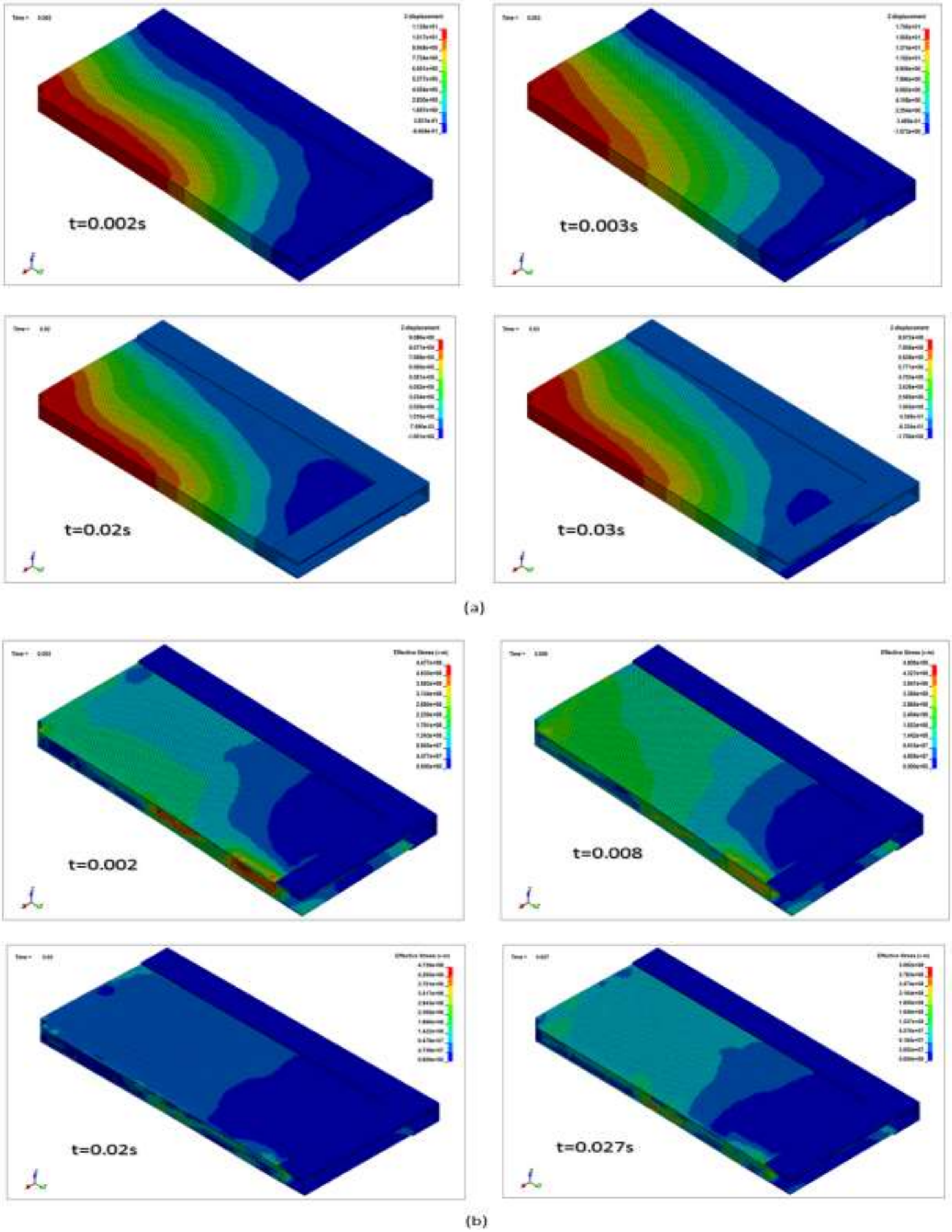

Fig. 10. Numerical simulated results: (a) displacement cloud diagrams, (b) Mises-stress cloud diagrams

Table 4. Summary of OSSA analysis results with different thicknesses of the second face sheet

Door type	Second face sheet thickness (mm)	Weight (kg)	μ	θ°
Optimized steel door without foam	0	120	7.77	5.36
OSSA	5	185	5.22	3.73
OSSA	2	150	5.57	4.32
OSSA	1	135	5.73	4.44

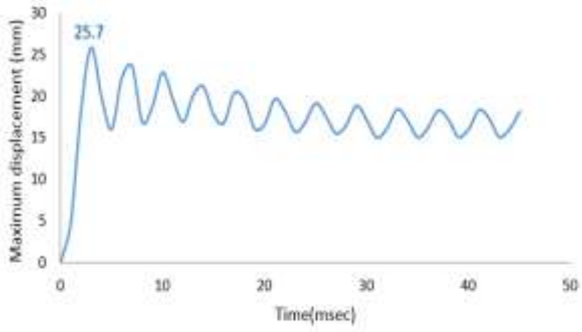

Fig. 11. The time history of maximum displacement of OSSA with a peak overpressure of 0.75MPa.

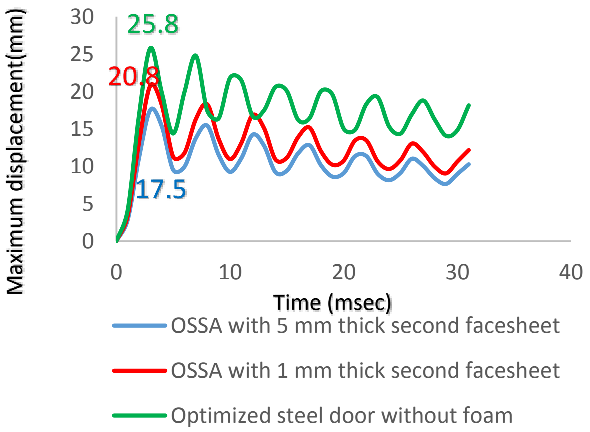

Fig. 12. The time variation of maximum displacement of the doors: OSSA with 5mm and 1mm thick second face sheet and optimized steel door without foam

4. Conclusions

In this study, the hierarchical stiffened impact-protective steel door was investigated. This door was relatively heavy, so it was optimized, and as a result, the door's weight was reduced by 42%. Then, to reduce the maximum displacement, the use of aluminum foam as a sandwich panel for the optimized stiffened steel door was proposed, which, depending on the thickness of the second face sheet, led to a 20 to 32% reduction in maximum displacement. The results showed that OSSA with 5mm thick second face sheet, under peak overpressure of 0.75MPa, has almost the same maximum displacement compared to the optimized steel door without aluminum foam under peak overpressure of 0.45MPa. In other words, using aluminum foam, the door can resist 67% more load with the same maximum displacement. Therefore, if impact-protective doors are needed in conventional buildings, the use of OSSA, presented in this paper, is recommended. Also, the OSSA can act as an insulator against sound and heat and is also resistant to the penetration of projectiles.

Therefore, the summary of the results obtained from this study can be listed as follows:

- Introducing an optimal door weighing 42% less than the primary door.
- Obtaining 20 to 32% reduction in maximum displacement by combining foam and stiffened door.

It is suggested for future studies to evaluate the performance of the OSSA door against the projectile penetration.

Appendix A-Validation

To validate the model used in this study, the SMC door designed by Zhang et al. (2018, b) was modeled in Ls-Dyna. The results of the analysis were compared with experimental and numerical results.

For modeling the SMC door, the MAT-ELASTIC model was employed. According to the experiments, the density was 1850kg/m^3. The elastic modulus was set as 7.1GPa and the Poisson's ratio was 0.32. The mesh dimension adopted for hexahedron solid elements was 1mm. Also, for modeling rigid frame made of steel, the MAT-RIGID model was adopted in which all displacements and rotations were constrained. The density was 7850kg/m^3 with 210GPa elastic modulus and 0.25 of Poisson's ratio.

The SMC door designed by Zhang et al. (2018, b) was investigated under two blast loads. The first load is that shown in Fig.13. The other one was that shown in Fig.1.b and measured in the experiment performed by Meng et al. (2016).

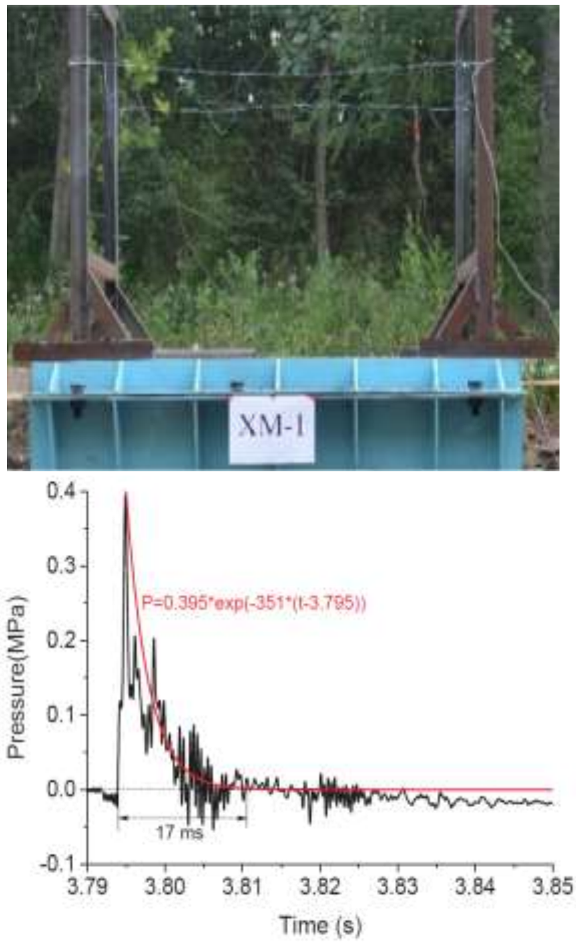

Fig. 13. Simplified blast wave curve according to the experiment performed by Zhang et al. (2018, b)

After modeling in Ls-Dyna, the maximum displacement value obtained from our analysis under the load shown in Fig.13 was 4.41mm at the central point of the door. However, the maximum displacement obtained from experiments performed by Zhang et al. (2018, b) was 3.84mm, and the maximum displacement obtained from the numerical results of Zhang et al. (2018, b) was 4.35mm.

Also, the maximum displacement value obtained from our analysis under the load shown in Fig. 1.b, was 28.09mm at the central point of the door. In comparison, the maximum displacement value obtained from the numerical results of Zhang et al. (2018, b) was 28.53mm.

Thus, as shown in Fig. 14, there is a close agreement between the results of our modeling in LS-DYNA with the experimental and numerical results performed by Zhang et al. (2018, b).

We also note that, compared to SMC door designed by Zhang et al. (2018, b), the OSSA presented in this study, with a 5-mm thick second face sheet has 39% less maximum displacement and the OSSA with a 1mm thick second face sheet has 27% less maximum displacement. Also, the optimized steel door without foam has 10% less maximum displacement than the door designed by Zhang et al. (2018, b) under the load shown in Fig. 1.b.

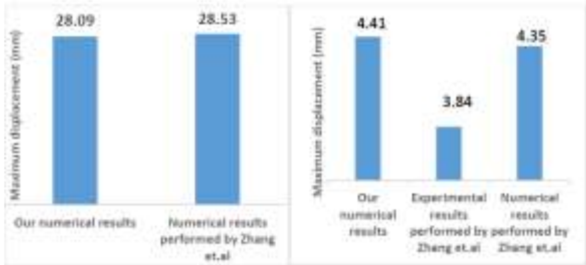

Fig. 14. Validation of the model used in this study (a) under the load shown in Fig. 9 and (b) under the load shown in Fig. 1.b.

References

Abbasi M, Nia AA, "High-velocity impact behavior of sandwich structures with AL faces and foam cores-Experimental and numerical study", Aerospace Science and Technology, 2020, Oct., 105(1), 106039 https://doi.org/10.1016/j.ast.2020.106039

Abedini M, Zhang C, "Performance assessment of concrete and steel material models in LSDYNA for enhanced numerical simulation, a state of the art review", Archives of Computational Methods in Engineering, 2021, 28 (4), 2921-2942. http://dx.doi.org/10.1007/s11831-020-09483-5

Cai S, Liu J, Zhang P, Li C, Cheng Y, "Dynamic response of sandwich panels with multi-layered aluminum foam/UHMWPE laminate cores under air blast loading", International Journal of Impact Engineering, 2020, 138, 1034-1075. https://doi.org/10.1016/j.ijimpeng.2019.103475

Chen D, Jing L, Yang F, "Optimal design of sandwich panels with layered-gradient aluminum foam cores under air-blast loading", Composites part B: Engineering, 2019, 166, 169-186. https://doi.org/10.1016/j.compositesb.2018.11.125

Chen G, Zhang P, Liu J, Cheng Y, Wang H, "Experimental and numerical analyses on the dynamic response of aluminum foam core sandwich panels subjected to localized air blast loading", Marine Structures, 2019, 65, 343-361. https://doi.org/10.1016/j.marstruc.2019.02.005

Darvizeh R, Davey K, "A transport approach for analysis of shock waves in cellular materials", International Journal of Impact Engineering, 2015, 82, 59-73. https://doi.org/10.1016/j.ijimpeng.2014.11.006

Fan HL, Jin FN, Fang DN, "Mechanical properties of hierarchical cellular materials. Part I: analysis", Composite Science and Technology, 2008, 68, 33803387. https://doi.org/10.1016/j.compscitech.2008.09.022

Ganchao C, Pan Z, Jun L, Yuansheng C, Hao W, "Experimental and numerical analyses on the dynamic response of aluminum foam core sandwich panels subjected to localized air blast loading", Marine structures, 2019, 65, 343-361. https://doi.org/10.1016/j.marstruc.2019.02.005

Goel MD, Matsagar Vasant A, Gupta AK, "Dynamic response of stiffened plates under air blast", International Journal of Protective Structures, 2011, 2, 139-156. https://doi.org/10.1260/2041-4196.2.1.139

Guzas EL, Earls CJ, "Air blast load generation for simulating structural response", Steel and composite structures, 2010, 10, 429-455. https://doi.org/10.12989/scs.2010.10.5.429

Hanssen AG, Hopperstad OS, Langseth M, Ilstand H, "Validation of constitutive models applicable to aluminum Foams", International Journal of mechanical Sciences Engineering, 2002, 44, 359-406. https://doi.org/10.1016/S0020-7403(01)00091-1

Jankowiak T, Rusinek A, Kpenyigba KM, Pesci R, "Ballistic behavior of steel sheet subjected to impact and perforation", Steel and Composite Structures, 2014, 16, 595-609. http://dx.doi.org/10.12989/scs.2014.16.6.595

Jen CY, Tai YS, "Deformation behavior of a stiffened panel subjected to underwater shock loading using the non-linear finite element method", Materials and Design, 2010, 31, 325-335. https://doi.org/10.1016/j.matdes.2009.06.011

Jianhu S, Guoxing L, Zhihua W, Longmao Z, "Experiments on curved sandwich panels under blast loading", International Journal of Impact Engineering, 2010, 37, 960-970. https://doi.org/10.1016/j.ijimpeng.2010.03.002

Koh C, Ang K, Chan P, "Dynamic analysis of shell structures with application to blast resistant doors", Shock and Vibration, 2003, 10, 26-97. https://doi.org/10.1155/2003/357969

Langdon GS, Karagiozova D, Theoblad MD, Nurick GN, Lu G, Merrett RP, "Fracture of aluminum foam core sacrificial cladding subjected to air-blast loading", International Journal of Impact Engineering, 2010, 37, 638-651. https://doi.org/10.1016/j.ijimpeng.2009.07.006.

Li S, Li X, Wang Z, Wu G, Lu G, Zhao L, "Sandwch panels with layered graded aluminum honeycomb cores under blast loading", Composite Structures, 2017, 173, 242-254. https://doi.org/10.1016/j.compstruct.2017.04.037

Liang M, Li Z, Lu F, Li X, "Theoretical and numerical investigation of blast responses of continuous-density graded cellular materials", Composite Structures, 2017, 164, 170-179. https://doi.org/10.1016/j.compstruct.2016.03.066

Liang MZ, Li XY, Lin YL, Lu FY, "Compaction wave propagation in layered cellular materials under air-blast", International Journal of Applied Mechanics, 2019, 11, 195-203. https://doi.org/10.1142/S1758825119500030

Liu H, Cao Zk, Yao GC, Luo HJ, Zu GY, "Performance of aluminum foam-steel panel sandwich composites subjected to blast loading", Materials & Design, 2013, 47, 483-488. https://doi.org/10.1016/j.matdes.2012.12.003

Louca LA, Pan YG, Harding JE, "Response of stiffened and unstiffened plates subjected to blast loading", Engineering Structures, 1998, 20, 1079-1086. https://doi.org/10.1016/S0141-0296(97)00204-6

Meng FM, Zhang B, Zhao Z, Xu Y, Fan HL, Jin FN, "A novel all-composite blast resistant door structure with hierarchical stiffeners", Composite Structures, 2016, 148, 113-126. https://doi.org/10.1016/j.compstruct.2016.03.066

Ngo T, Mendis P, Gupta A, Ramsay J, "Blast loading and blast effects on structures–an overview", Electronic Journal Of Structural Engineering, 2007, 1, 76-91. https://doi.org/10.56748/ejse.671

Nurick GN, Olson MD, Fagnan JR, "Deformation and tearing of blast loaded stiffened square plates", International Journal of Impact Engineering, 1995, 16, 273-291. https://doi.org/10.1016/0734743X(94)00046-Y

Nurick GN, Shave GC, "The deformation and tearing of thin square plates subjected to impulsive loads-an experimental study", International Journal of Impact Engineering, 1996, 18, 99-116. https://doi.org/10.1016/0734-743X(95)00018-2

Palta E, Gutowski M, Fang H, "A numerical study of steel and hybrid armor plates under ballistic impacts", International Journal of Solids and Structures, 2018, 1, 136, 279-294. https://doi.org/10.1016/j.ijsolstr.2017.12.021

Rashad M, Yang TY, "Numerical study of steel sandwich plates with RPF and VR cores materials under free air blast loads", Steel and Composite Structures, 2018, 27, 717-725. https://doi.org/10.12989/scs.2018.27.6.717

Rudrapatna NS, Vaziri R, Olson MD, "Deformation and failure of blast-loaded stiffened plate", International Journal of Impact Engineering, 2000, 24, 457-474.

https://doi.org/10.1016/S0734743X(99)00172-4

Santosa SP, Arifurrahman F, Izzudin MH, Widagdo Gunawan L, "Response analysis of impact blast loading of Metal-Foam sandwich panels", Procedia Engineering, 2017, 173, 495-502. https://doi.org/10.1016/j.proeng.2016.12.073

Shrivastava S, Tiwari G, Iqbal MA, Gupta PK, "The ballistic performance of thin aluminum plates against blunt-nosed projectile", Materials Today: Proceedings, 2020 Jan, 1, 21, 1763-1771. https://doi.org/10.1016/j.matpr.2020.01.229

Sławiński G, Malesa P, Świerczewski M, Bogusz P, "Experimental and numerical investigation of connector with elastomer joint", Journal of Kones, 2017, 24, 17-20. http://dx.doi.org/10.5604/01.3001.0010.3094

Sui QQ, Jiang S, Sun FF, Fan HL, "Mechanical analysis of hierarchical isogrid sandwich plate", Acta Mater Composite Sinica, 2016, 33, 675-680. https://doi.org/10.13801/j.cnki.fhclxb.20150911.001

Sun FF, Lai CL, Fan HL, "Crushing mechanism of hierarchical lattice structure", Mechanics of Materials, 2016, 97, 164-183. https://doi.org/10.1016/j.mechmat.2016.02.016

Tavakoli HR, Kiakojouri F, "Numerica l dynamic analysis of stiffened plates under blast loading", Latin American Journal of Solids and Structures, 2014, 11, 185-199. https://doi.org/10.1590/S167978252014000200003

Veeredhi LSB, Rao NVR, "Studies on the Impact of Explosion on Blast Resistant Stiffened Door Structures", Journal of the Institution of Engineers (India) Series A, 2015, 96, 11-20. http://dx.doi.org/10.1007/s40030-014-0103-x

Wang B, Tian K, Hao P, "Hybrid analysis and optimization of hierarchical stiffened plates based on asymptotic homogenization method", Composite Structures, 2015, 132, 136-147. https://doi.org/10.1016/j.compstruct.2015.05.012

Wang B, Tian K, Zhou CH, "Grid-pattern optimization framework of novel hierarchical stiffened shells allowing for imperfection sensitivity", Aerospace Science and Technology, 2017, 62, 114-121. https://doi.org/10.1016/j.ast.2016.12.002.

Wei L, Yang B, Yongxiang D, Shunshan F, "Dynamic response of spherical sandwich shells with metallic foam core under external air blast loading-Numerical Simulation", Composite Structures, 2014, 14, 00225-4. https://doi.org/10.1016/j.compstruct.2014.05.038

Xie Z, Yan Q, Li X, "Investigation on low velocity impact on a foam core composite sandwich panel", Steel and Composite Structures, 2014, 17, 159-172. https://doi.org/10.12989/scs.2014.17.2.159

Xu WL, Wang C, Yuan JM, Deng T, "Bore-center annular shaped charges with different liner materials penetrating into steel targets", Defence Technology, 2019 Oct, 1, 15 (5), 796-801. https://doi.org/10.1016/j.dt.2019.07.001

Yurddaskal M, Baba BO, "The effect of curvature on the impact response of foam-based sandwich composite panels", Steel and Composite Structures, 2016, 20, 983-997. https://doi.org/10.12989/scs.2016.20.5.983

Zhang B, Zhao Z, Zhou ZX, Chen HL, Fan HL, Jin FN, "Hierarchical anisogrid stiffened composite panel subjected to blast loading: equivalent theory", Composite Structures, 2018a, 187, 259-268. https://doi.org/10.1016/j.compstruct.2017.12.059

Zhang B, Zhao Z, Zhou ZX, Chen HL, Wang B, Zhou Y, Xu Y, Jin FN, Fan HL, "Quasi-far-field blast response of hierarchical orthogrid-stiffened sheet molding compound (SMC) protective door", Engineering structures, 2018b, 168, 431-446. https://doi.org/10.1016/j.engstruct.2018.05.001

Zhang B, Hailong C, Ming L, Zheng Z, Yinzhi Z, Hualin F, "Equivalent static load method for hierarchical stiffened composite panel subjected to blast loading", Engineering Structures, 2018c, 171, 569-582. https://doi.org/10.1016/j.engstruct.2018.05.107

Zheng C, Kong XS, Wu WG, Liu F, "The elastic-plastic dynamic response of stiffened plates under confined blast load", International Journal of Impact Engineering, 2016, 95, 141-153. https://doi.org/10.1016/j.ijimpeng.2016.05.008

Zhang J, Qin Q, Wang T, "Compressive strengths and dynamic response of corrugated metal sandwich plates with unfilled and foam-filled sinusoidal plate cores", Acta Mech, 2013, 224, 759775. http://dx.doi.org/10.1007%2Fs00707-012-0770-5