Advanced Structural Mechanics 1 (2023) 133-144

Advanced Structural Mechanics

journal homepage: http://asm.sku.ac.ir

Investigating the performance of steel plate equipped with unidirectional epoxy reinforced glass fibers against TNT explosives

Hamid Sattarian Karajabad[a,*], Milad Arjomand[b]

[a]PhD student at Shiraz University of Technology, Department of Civil and Environmental Engineering, Shiraz, Iran
[b]M.Sc Civil and Hydraulic Structures, Semnan University, Semnan, Iran

Article received:2023/01/01, Article revised: 2023/02/15, Article accepted: 2023/02/18

ABSTRACT

Research on increasing the materials' resistance against impact, force, and heat is always of interest to researchers. This factor is of double importance in the structural engineering and type of use of the structure. This research aims to discuss an increase in resistance against the explosion on the steel shear wall, which is considered as one of the industrial and military structures. Due to the characteristic of the positive performance of epoxy glass fibers caused by reinforcing the steel plate with this type of fibers against the explosive substance, the performance of the steel shear wall is analyzed as a simulation based on the finite element method in Abaqus software.
The results of the research show that epoxy-reinforced glass fibers can reduce the plate displacement due to the reduction of strain energy in the steel plate and decrease the absorption amount of the resulting energy, which is in the form of an explosion wave. Finally, with the absorption of energy by epoxy reinforced glass fibers, the least buckling is observed with an increase in the thickness of the fibers and also the least amount of stress against the explosive material. The results show the very favorable effect of epoxy reinforced glass fibers in improving the resistance of composite steel plates against blast.
Keywords: Blast, strengthening, composite, steel plate, finite element model

1. Introduction

The design of the resistant structures has always been the main concern for engineering. Many existing structures are vulnerable to the loads caused by the blast waves, and therefore, their resistance against such loads should be increased. Various types of research have thus been conducted in this area to increase the stability and durability of

* Corresponding author at: Department of Civil and Environmental Engineering, Shiraz, Iran.
E-mail address: h.sattarian@sutech.ac.ir.

DOI: 10.22034/asm.2023.14201.1009: https://asm.sku.ac.ir/article_11389.html

structures against destructive factors. Considering the type of use of the structure, cost and weight of the structure are two prominent influential factors affecting the design. There are existing and standard solutions to increase the structure's resistance against the loads caused by impact and blast. Among the most important of them we can refer to the use of local reinforcement, such as steel coatings and concrete coatings for structural members, as well as the addition of new structural systems like composite steel shear wall. This method has some disadvantages: firstly, it imposes significant gravity loads on the structure, and finally, the foundation, and on the other hand, it requires much time for installation, as a result, cannot be economically viable.

According to the nature of usage, the types of structures, such as military and other important structures that are considered vital arteries, are more critical against destructive factors in order to provide uninterrupted services. These types of structures' reinforcement have thus been investigated and various research studies have been conducted in this area. Fiber reinforced polymers (FRPs) are one of the ideas used by combining several different materials to increase resistance against any type of applied stress, such as impact and waves caused by blast and heat, etc. FRP composites have been used for more than six decades in the structural engineering in construction, retrofitting, strengthening, repair, and improvement of existing structures. During the last decade, there has been significant growth in the use of FRP materials, an advanced type of composites. FRP composite materials consist of high-strength fibers embedded in a polymer matrix. Fibers in an FRP composite are the primary load-bearing member and show very high strength and stiffness as long as they are in tension [1].

1.1. FRP Fibers

FRP materials include fibers with high resistance in a polymer field; fibers are considered the primary load-bearing members and have very high resistance and stiffness during tension. As shown in Fig. 1, the polymer in the fibers is found to cause stress distribution in the fibers while preventing the damage to the fibers.

Due to the consideration of various applied stresses in terms of their military importance, military structures, including warehouses and buildings, etc., may always be added to the bearing lateral forces, such as the earthquake force. In case of vandalism, such as explosions and fire, they will also face heat and blast waves. For this purpose, the use of composite materials with the required resistance against these stresses is discussed. FRP fibers are used in different ways; one of them is the use of fiber reinforcement plates. Fiber plates applied to the main structure reduce deformations (increase stiffness), limit cracking and breakage phenomena (increase durability), and increase load capacity and breaking load (increase safety). Regarding the use of steel structures in military centers to better compare the behavior of fibers with steel plate, the following points can be briefly mentioned:

- High characteristic stiffness and resistance compared to steel
- Long service life
- Corrosion resistance
- Controllable thermal property

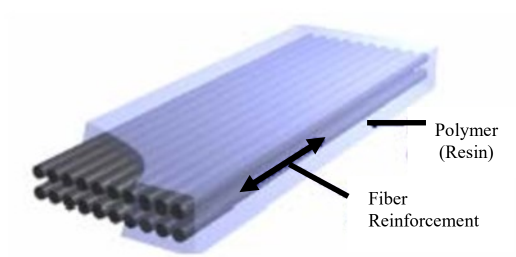

Fig. 1. A cross-section of fiber components [2]

1.2. Glass Fibers

One of the fibers used in the military and other industries is glass fiber. Glass fibers are one of the most essential reinforcing materials and the most common ones with a polymer matrix background. Fibers make up a considerable volume of a composite. Their primary function is to bear the load applied to the composite. The type of fibers, their amount, and arrangement, are very essential and affect the properties. The internal structure of these fibers consists of an extended three-dimensional network of silicon, oxygen, and other atoms that are randomly arranged. Therefore, glass fibers are non-crystalline and anisotropic. The flexibility, corrosion resistance, and high fatigue resistance of glass have made it to be widely used in many structures. Moreover, the suitable tensile strength of glass fibers makes these fibres to be used in pressure vessels, rockets, rubber, and other structures [3].

1.3. Epoxy Resin

One of the reinforced composites is the use of epoxy resin along with glass fibers. Polymer materials used in the field of composite materials are called resin. Resins by themselves do not have enough strength to be used in structural components, but they can be used as structural components of composite materials with high strength and low weight when used as a matrix and reinforced by other materials. Resins are divided into two categories: thermoplastic and thermoset. Epoxies have high properties and performance. One of their most important features is their very high hardness and resistance, high heat resistance, excellent adhesion, and good chemical resistance, especially in alkaline environments [4].

1.4. Blast

A blast is a chemical reaction that causes a very rapid release of energy in light, heat, sound, and waves. When a blast occurs, energy is released suddenly and in a concise time (a few milliseconds). The effect of this release of energy is observed in the form of thermal radiation and propagation of waves in space. The high speed of its occurrence causes drastic changes in the behaviour of the structure and its surrounding environment [5]. Compared to other risks and loads on the building, such as earthquake and wind, the load caused by a blast has characteristics and differences that must be taken into consideration:

- The pressure on the building during a blast can be many times greater than the pressure caused by other hazards.
- The pressure caused by the blast dissipates very quickly. For this reason, the destruction caused by the blast in the part of the structure that is about to explode will be much more severe than the back of the structure [6].
- The time interval and consequently the loading period in the blast are concise, which usually occurs in a few thousandths to a few hundredths of a second. While the duration of the earthquake load is several tens of seconds and the duration of the wind load varies up to several tens of minutes [7].
- Generally, factors such as the explosion magnitude in TNT scale, distance from the center of the explosion to the structure, geometry and structural system, and angle of the structure in line with the movement of the wave and the ground are taken into consideration in the evaluation of the explosion effect on building [8].

Steel is one of the materials that are widely used in structures. Steel is widely used in the structure of buildings and industry. For this reason, investigating and knowing its behaviour under explosive loads can be beneficial. In the industry, these plates are used in construction of power transformers and explosion protection of facilities and objects. The previous research studies have shown that ductility materials even with lower resistance have a much better performance against explosive loading [9].

Astana et al. investigated the impact of the explosion caused by the vehicle on their proposed wall, a combination of steel and concrete shear walls. Ordinary concrete walls are crushed under the effect of an explosion, and its particles are spread in the environment at a very high speed. These fragments themselves can cause severe damage and casualties. However, in this type of wall, a steel plate behind the wall prevents the movement of concrete particles and removes this risk. This wall consists of a steel plate welded to the frame, and then reinforced concrete slabs are installed on it using bolts and nuts [10].

Jin Sun and Astana investigated the performance of bridge decks with different materials against the blast loads caused by vehicle explosions. In this research, the bridge deck was investigated in two cases, including steel box and composite. The results indicated that steel and concrete materials with lower strength and greater flexibility performed better [11].

Mojtahdpour et al. investigated the performance of steel wall against blast loading and reinforced the wall by using stiffener. In this research, the manner and value of the distribution of parameters such as displacement and stress for the steel wall in different states of thickness and hardening have been calculated and compared [9].

Azarbaijani et al., analysed two shear walls, one of which was an ordinary reinforced concrete shear wall and the other was a composite one. They investigated the performance of the walls against blast loading. The results showed that using composite walls significantly increases the building's explosion resistance, while the cost of the structure does not increase. Moreover, they found an increase in the thickness of steel plates does not have a significant effect on increasing the strength of the wall. Considering the costs caused by increasing the thickness and especially the implementation problems, the optimal thickness of the plates is 12 mm. [12].

Luccioni is another researcher who has conducted many studies in the field of explosion. In one of these research studies, in 2006, the behaviour of concrete slab under the effect of blast load was investigated.

At first, he subjected the concrete slab to the explosive load in a laboratory and then compared the obtained results with modelling by ABAQUS and ANSYS software and after showing the accuracy of the modelling, he tried to provide a relationship between the diameter of the hole caused by the explosion, the weight of the explosives and the location of the explosion and at the end, he made a comparison between the used experimental and numerical models. They explained their strengths and weaknesses in each case, and investigated the behaviour of steel and concrete structures with different shapes and conditions under blast loading and simulated and compared the effect of shape and other characteristics on the structure performance for both steel and concrete types by finite element software. They reported the performance of concrete structures to be more appropriate in general [13].

Some structures such as power plants, government buildings and embassies must be strengthened against the blast load. One of the simple ways to do this is to use protective walls or anti-explosion walls, which can be used for both existing buildings and buildings under construction. A wall can prevent a part of the wave from reaching the main structure by creating an obstacle between the source of the explosion and the structure. In addition, when the wave hits the wall, the reflection of the wave occurs and the reflected wave acts as a barrier for that part of the wave that reaches the structure. Both experimental research and numerical simulation have shown that the use of a protective wall has an influential role in reducing the blast wave.

Relying on the development of new numerical methods, in addition to laboratory methods, researchers have extensively worked on modelling and numerical methods. Those can refer to the experiments conducted by Ishikawa regarding the effect of the guard wall on the wave propagation path [14]. After that, the computer modelling done by Zhou and Hao provided valuable formulas for calculating the effect of the guard wall in the path of the blast wave [15].

1.5. Explosive load

According to the location of the explosive, explosions are divided into two categories: enclosed explosion (internal) and non-enclosed explosion (external).

Non-enclosed explosions are categorized as open-air explosions, air explosions, and surface explosions.

Enclosed explosions are divided into three categories based on the type of the structure: fully vented, semi-enclosed, and enclosed [16].

1.6. Maximum impact pressure due to explosion

National Building Regulations, Section 21; to determine the maximum impact pressure caused by an explosion in the open air for medium and long distances, broad relations, and for the distances close to the field, Henrich's relations have been proposed, which are in good agreement with the experimental results [17].

1.7. Steel behavior under the effect of strain rate

Considering the collision of the blast wave with the steel plate and the sensitivity of the investigation of the strain resistance in steel, the behavior of steel under the effect of strain rate is also discussed. The modulus of elasticity of steel is independent of strain rate effects and always has a constant value during loading. The yield strength and ultimate strength of steel depend on the strain rate affects such that the amount of yield strength and ultimate strength increases with the increase of the strain rate.

Equation (1) shows the effect of strain rate on the yield strength of steel:

$$DIF^{y}_{steel} = \frac{f_y}{f_{y,st}} = (\frac{\varepsilon^{\bullet}}{\varepsilon^{\bullet}_{st}})^{a_y} \quad (1).$$

Equation (2) shows the effect of the strain rate on the ultimate strength of steel:

$$DIF^{u}_{steel} = \frac{f_u}{f_{u,st}} = (\frac{\varepsilon^{\bullet}}{\varepsilon^{\bullet}_{st}})^{a_u} \quad (2).$$

Where f_y is the dynamic yield stress related to $\dot{\varepsilon}$ and $f_{y,st}$ is the static yield stress and f_u is the dynamic yield stress related to $\varepsilon^{\bullet}$, $f_{u,st}$ is the ultimate static strength of the steel and $\varepsilon^{\bullet}_{st}$ is the static strain rate [18].

2. Numerical analysis

Due to the limitations such as the cost of the experiments and considering the laboratory facilities and safety, the use of numerical software is today considered a desirable option for validating and checking different ideas in all scientific aspects. Therefore, ABAQUS software has been used in this research to analyze the models.

First, to validate the numerical model by focusing on the behavior of the steel shear wall, the experimental model of Wayne and Bruneau [19], which is a one-span frame of steel shear wall, is simulated with ABAQUS software. Figure. 2, shows the experimental and numerical models.

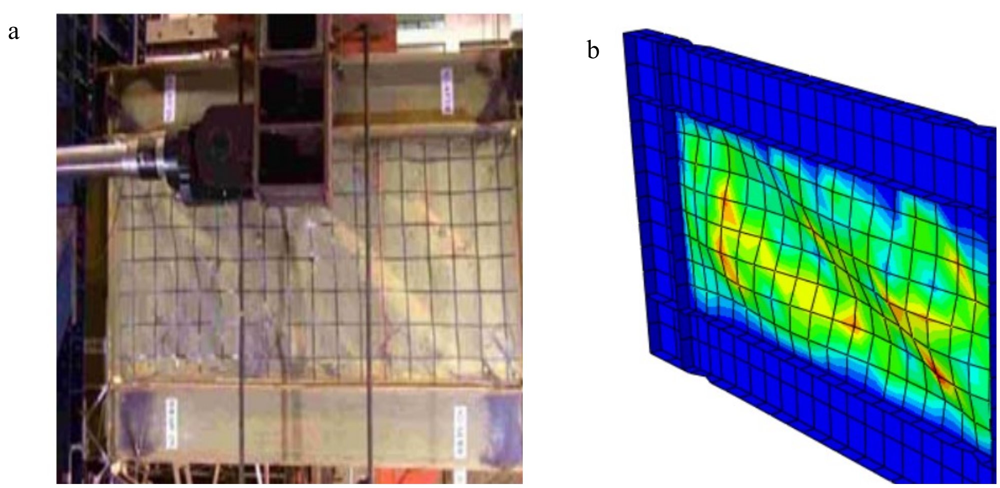

Fig. 2. (a) experimental; (b) numerical model

The analyzed numerical model is aligned with the experimental model of Vienna and Bruneau, for the LYS steel plate. The yield stress and the ultimate stress are, respectively, equal to 165 and 305 MPa. The thickness of the beam and column members of the frame is 2.6 mm according to the ASTM A572 standard. GR50 with W18*65 and W18*71 sections with yield stress and ultimate stress of 345 and 480 MPa has been considered.

Due to the low ratio of one direction compared to other dimensions, the loose element was used for modeling. The effect of the geometric non-linear behavior of materials is also considered in the modelling. To apply the effect of the jacks holding the columns in the software, the wire element was used. The connection type is considered to be a Connector Beam. This type of connection has the property of being rigid. It includes the transfer of all the axial and rotational forces in the connection areas [20]. The type of loading is quasi-static by applying cyclic displacements. To observe the non-linear behavior in the model caused by the absence of buckling in the steel plate due to the type of loading and the location of the load, the initial defect (imperfection) is needed to be applied by creating a minor defect in the structure of the part (imperfection). At first, the buckle analysis model was applied. The initial defect of the samples, according to Fig. 3, is equal to the first buckling mode.

Finally, to validate the numerical model, the results of the experimental model were compared with the numerical model. As shown in Fig. 4, according to the matching of the peak cover curve of each cycle resulting from the cyclic loading of the numerical model with the experimental model, finally, the explosion behavior for steel plates with glass fibers reinforced with epoxy is discussed.

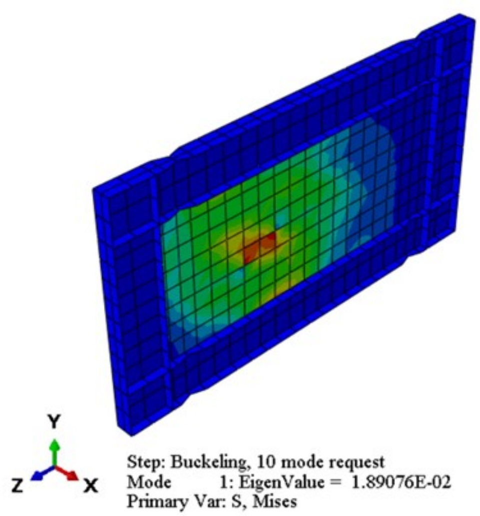

Fig. 3. The first mode of buckling in the steel plate resulting from the buckling analysis to apply the imperfection property to the plate

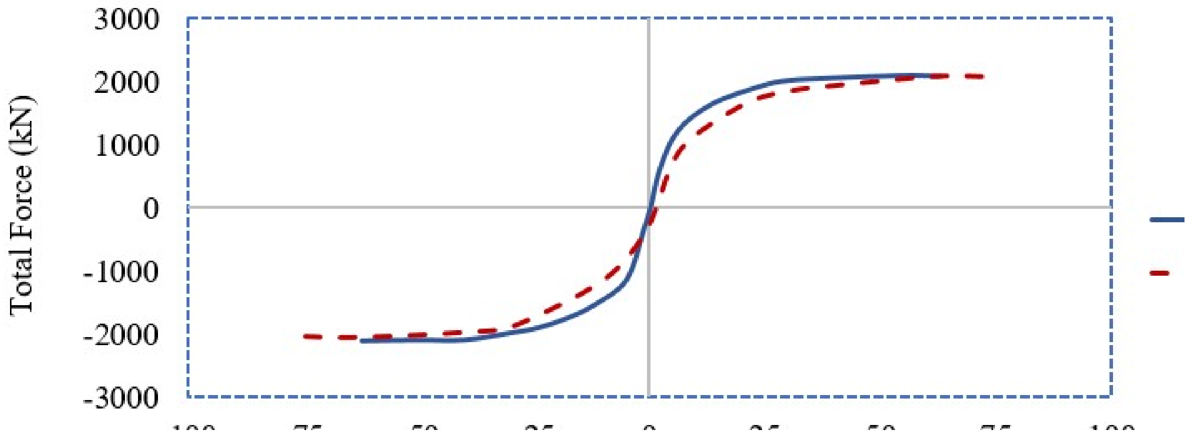

Fig. 4. According the cover curve of the numerical model with the experimental model

3. Results and discussion

In this research, unidirectional glass fibers have been used, which have low weight and high strength, and the orientation of the fibers is in the direction of zero degrees. Compared to unidirectional carbon fibers, unidirectional glass fibers have lower tensile strength and lower price, and this factor has caused glass fibers to be sold more than carbon fibers. Due to the high strength and light weight of unidirectional glass fibers, they are used in various fields and industries. The most common use of unidirectional glass fibers is in the construction industry. These fibers are used to strengthen buildings and industrial structures, strengthen all types of pipes and tanks, protect various components in corrosive environmental conditions, etc. Unidirectional glass fibers have good compatibility with all kinds of glues and chemical resins, including epoxy resin and polyester resin. They can be attached to all kinds of different surfaces by using them. For this purpose, this property has been applied in the software according to Table (1), for the models.

After matching the laboratory model with the numerical model, the correct analysis process was conducted based on the loading by explosion method, in line with the experimental model of Guzas et al. [21]. According to Fig. 5, the loading of explosion by CONWEP method and the amount of explosive substance (TNT material) is equal to 1.36 kg of TNT at intervals of 1 meter and 1.53 meter the center of the steel plate is used.

Table 1. An example of applying the effect of unidirectional fibers for the studied numerical models.

Ply name	Region	Material	Thickness (mm)	CSYS	Rotation Angle	Integration Points
Ply-1	(picked)	Gfrp	0.003	<Layup>	0	3

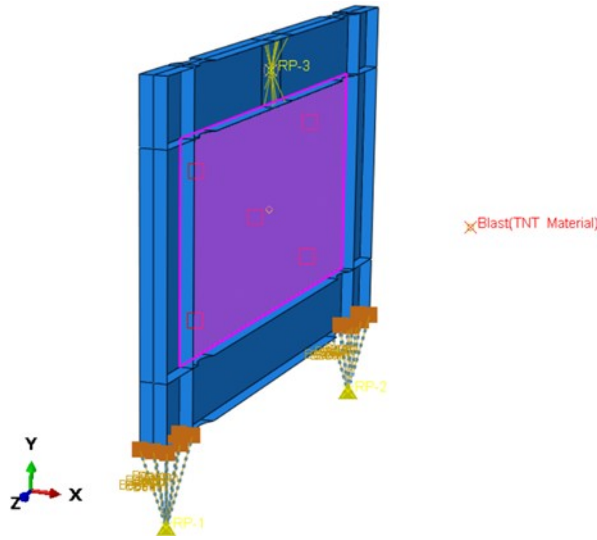

Fig. 5. The location of the explosive material (blast) along with the place of impact in the steel shear wall of the studied model

Finally, steel shear walls equipped with glass composite fibers with epoxy resin were analyzed against TNT explosives[22]. Table (2) is presented in order to understand the analysis process of the models.

Table 2. Analysis process of the studied models

MODELS	Displacement(m)		GFRP With Epoxy thickness(m)		
	1.53	1	0.002	0.003	0.004
SPSW-1	*				
SPSWGF-2	*		*		
SPSWGF-3	*			*	
SPSWGF-4	*				*
SPSW-5		*			
SPSWGF-6		*	*		
SPSWGF-7		*		*	
SPSWGF-8		*			*

Among the analyzed models, SPSW-1 and SPSW-5 models without fibers and other models were analyzed according to Table (1) based on the thickness of GFRP fibers and the distance of the explosive material.

Next, in order to better understand the results of the analysis, the graphic model of the amount of displacement due to the applied stresses caused by the blast wave on some of the studied models is presented in Fig. 6.

Finally, According to Fig. 7, the output of the models is presented based on the amount of displacement of the center of the steel plate (Displacement Center), the energy absorbed in the steel plate (ALLIE) and the strain energy of the steel plate (ALLSE).

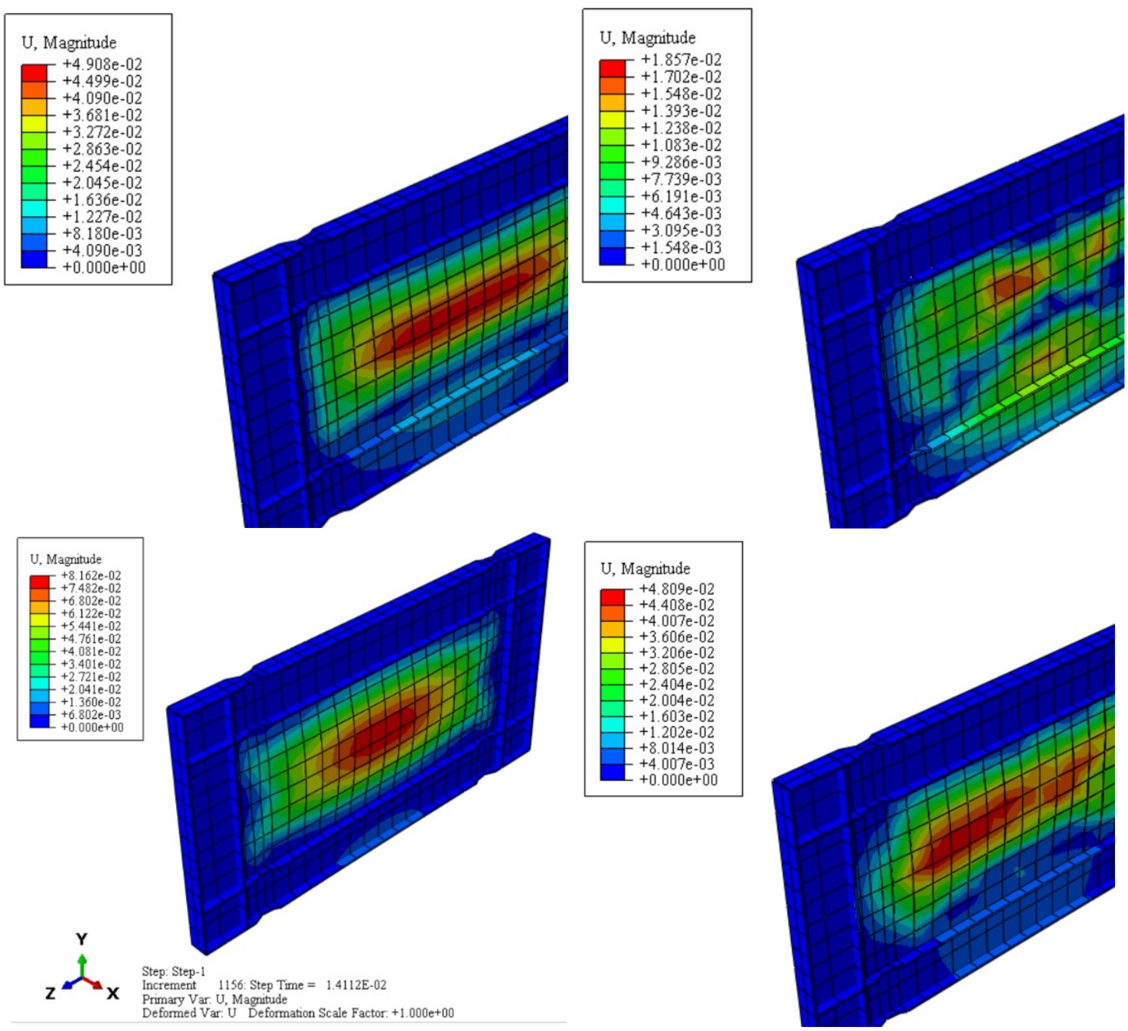

Fig. 6. Comparison of the amount of displacement of the studied models due to the impact of the wave caused by the explosion along with the effect of reinforcing fibers

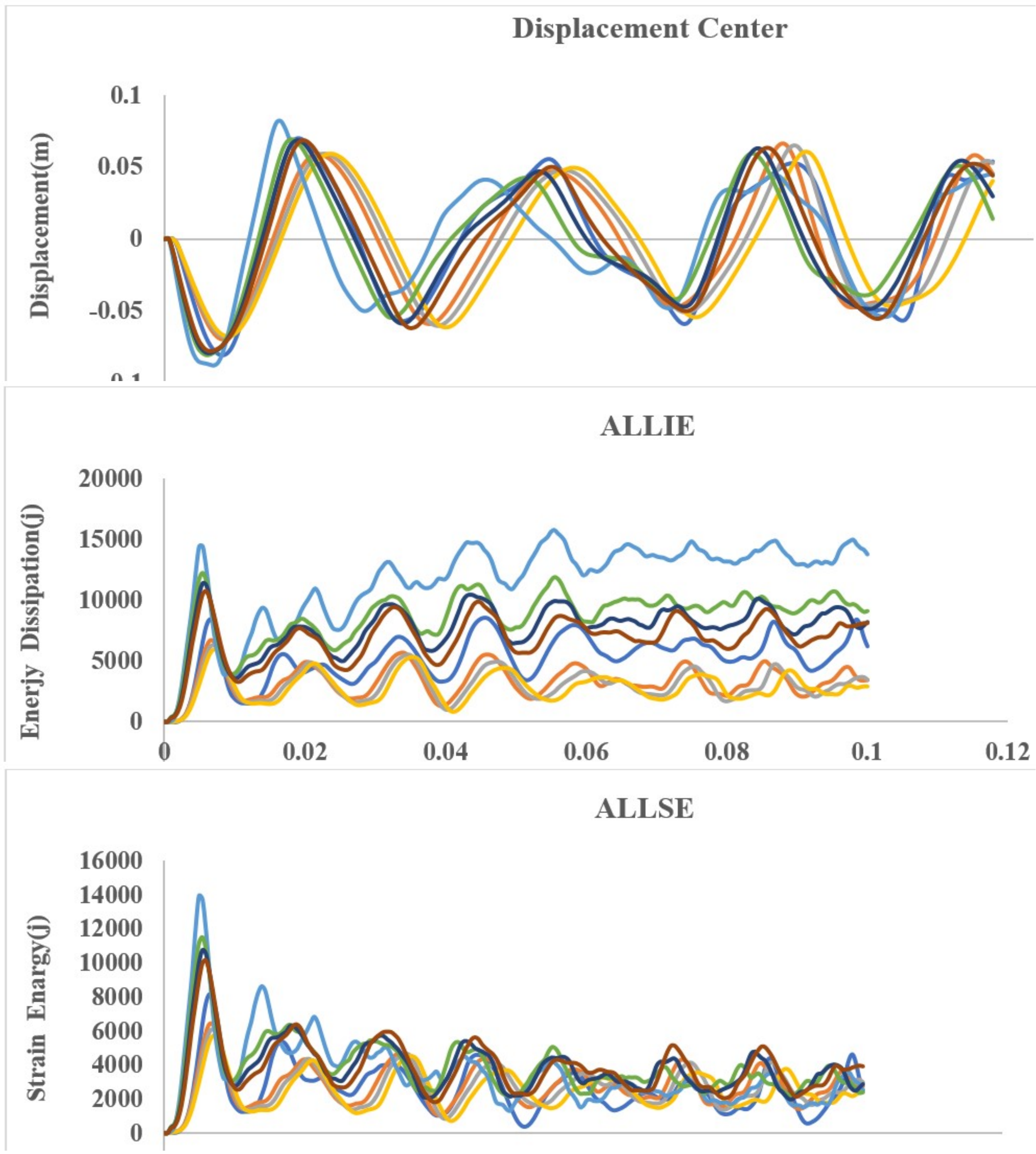

Fig. 7. The curve of the amount of displacement of the center of the steel plate and the amount of absorbed energy and strain energy in the steel plate of the analyzed models

According to the displacement values of the center of the steel plate, finally, the maximum displacement values of the center of the steel shear wall plate are presented in Table (3).

Table 3. Maximum displacement values of steel shear wall plate

Models	Time (s)	Max Displacement(m)
SPSW-1	0.007	0.080
SPSW-5	0.006	0.088
SPSWGF-2	0.007	0.070
SPSWGF-3	0.007	0.069
SPSWGF-4	0.007	0.067
SPSWGF-6	0.005	0.081
SPSWGF-7	0.005	0.079
SPSWGF-8	0.005	0.078

4. Conclusion

In this research, glass fibers have been used along with epoxy reinforcement in SPSW to increase the strength of the steel plate and reduce the amount of buckling and strain of the plate against the explosive material. According to the properties of glass fibers and the nature of the explosive material, glass fibers were applied unidirectionally with steel plate and finally, the models were analyzed based on the thickness of the fibers and the distance of the explosive material, the results are presented as follows:

- As can be seen, SPSW-1 and SPSW-5 models are without epoxy fiber-reinforced material. According to the distance and volume of the explosive material and considering the nature of the explosion wave, the maximum amount of displacement related to the SPSW-5 model was observed in the center of the steel plate within 0.006 seconds.
- The changes in steel plate strain show that the highest strain and resulting strain energy is created on the steel plate in the SPSW-5 model at the initial moment of the explosion. Also, the SPSWGF-4 model has the lowest amount of strain energy due to the thickness of GFRP fibers and the blast distance.
- The changes in steel plate strain show that the highest strain and resulting strain energy is created on the steel plate in the SPSW-5 model at the initial moment of the explosion. Also, the SPSWGF-4 model has the lowest strain energy due to the thickness of GFRP fibers and the blast distance.
- According to the distance of the explosive material and not using GFRP fibers in the steel plate, the results show that the SPSW-5 model has the highest energy receipt. The thickness of GFRP fibers based on the distance of the explosive material shows that increasing the thickness of the fibers reduces the impact of the explosion on the steel plate in creating internal force.
- According to the explosive material distance for SPSWGF-3 and SPSWGF-4 models and considering the thickness of GFRP fibers and the positive effect of fibers in reducing the amount of energy applied to the steel plate, the results showed that the steel plate, in this case, has the lowest amount of absorbed energy.
- By examining the strain energy curve, it is observed that according to the strength of the explosion wave, the highest amount of applied strain energy occurs at the very first moment of the explosion on all the studied models.

- The results show that the higher the amount of energy absorbed in the plate, the greater the amount of applied strain energy in the plate. Finally, it is observed that the strain has directly correlates with the amount of applied energy.
- For all studied models, it can be seen that the ratio of the distance of the explosive material and the amount of the explosive material have a direct relationship with increasing the amount of strain energy and the amount of displacement. Also, with the increase in the thickness of the fibers, the amount of displacement in the center of the plate has also decreased.
- Considering the amount of absorbed energy based on the thickness of the composite material and the distance of the explosive material, an increase in the thickness of the composite material has a positive effect on reducing the amount of stress applied to the steel plate.

Acknowledgments

During this research, unfortunately, one of the authors of this article, engineer Mr. Milad Arjomand, passed away. On this basis, to honor his name, all the spiritual achievements of this research are dedicated to his great soul.

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