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The Behavior of Lateral Crushed of Corrugated Composite Plates

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سلوك التكسير الجانبي للألواح المركبة المموجة

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Abstract

An experimental investigation was conducted to compare the crash characteristics and energy absorption capacity of a series of composite plate specimens with different corrugation profiles, these are sinusoidal triangles, and squares with flat composite plates placed at the top and bottom of corrugated plates. All these specimens were fabricated from glass fibers with the hand layup technique. Each profile has three different types of specimens: single plates, double plates, and triple plates. The corrugated plates are fixed over each other and subjected to the same kind of compression load. All these models have been exposed to lateral crushing load and then the collapse of these models has been observed and the results have been recorded. Finally; all the results obtained in this research were recorded and discussed. It is found that the highest value of specific energy of absorption was (1.579 kJ/kg) recorded for the level two square profile specimen. However, the lowest value (0.401 kJ/kg) was recorded for the level one sinusoidal profile specimen.

Keywords: *Composite plates, Energy absorption, Crashworthiness, Lateral crushing*.

الملخص

تم إجراء دراسة تجريبية لمقارنة خصائص التكسير وقدرة امتصاص الطاقة لسلسلة من عينات الألواح المركبة ذات أشكال تمويج مختلفة وهي: جيبية، ومثلثة، ومربعة مع ألواح مركبة مسطحة موضوعة في أعلى وأسفل الألواح المموجة. تم تصنيع كل هذه العينات من ألياف زجاجية بتقنية وضع اليد. يحتوي كل ملف تعريف على ثلاثة أنواع مختلفة من العينات: لوحة مفردة، ولوحات مزدوجة، ولوحات ثلاثية. يتم تثبيت الألواح المموجة فوق بعضها البعض وتخضع لنفس النوع من حمل الضغط. كل هذه النماذج تعرضت لحمل تكسير جانبي ومن ثم تم ملاحظة انهيار هذه النماذج وتم تسجيل النتائج. أخيرا؛ تم تسجيل ومناقشة جميع النتائج التي تم الحصول عليها في هذا البحث. لقد وجد أن أعلى قيمة للطاقة النوعية للامتصاص كانت (1.579 kJ/kg) مسجلة لعينة المربع مزدوجة اللوحات. ومع ذلك، تم تسجيل أدنى قيمة (0.878 kJ/kg) للعينة الجيبية ذات اللوحة الواحدة.

الكلمات الدالة: الألواح المركبة، امتصاص الطاقة، القدرة على التحطم، التكسير الجانبي.

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1. Introduction

Energy absorption characteristics are one of the most important considerations in selecting materials for many engineering applications, such as crushing elements in cars, bicycle helmets, hard hats used in construction sites, and protective packaging of fragile goods (Xue *et al*., 2000). There have been a number of studies that investigate the effect of corrugated geometry on the behavior of isolated corrugations (Fraser *et al*., 2020; Elbkory and Al ssahly, 2018; Fraser *et al*., 2014; Bouaziz, 2013; Dayyani *et al*., 2012; Boke, 2012; Thill *et al*., 2010; Ge *et al*., 2010; and Chiskis & Parnes, 1998). With regard to the composite materials with a corrugated reinforcement geometry, it is of interest to determine under what conditions the use of a corrugated geometry improves the necking strain of the composite. The effect of material properties has been explored for corrugated composites inelastic systems by Khatam and Pindera (2012), Chiskis and Parnes (1998), and Chou and Takahashi (1987). Abdurrahman and Nayfeh [13] used analytical micromechanical modeling to predict the stress distribution within a corrugated fiber reinforcement in an elastic matrix, providing valuable information on the local stress state in the composite material, although the model was limited to elastic materials and did not provide results on the global stress-strain behavior of the composite. Looking back implementation of composite materials in the field of crashworthiness is attributed to Hull, who in the 1980s and 1990s has studied extensively the crushing behavior of fiber-reinforced composite material. He found that the composite materials absorb high energy in the face of the fracture surface energy mechanism rather than plastic deformation as observed for metals (Shi *et al*., 2012; and Abdelrahman & Nayfeh, 1998)

The purpose of this paper is to experimentally investigate the effect of Corrugation geometry and shape on energy absorption of composite plates with flat composite plates placed at the top and bottom of corrugated plates. Three different corrugation profiles are tested which are sinusoidal, triangle and square. Subjected to quasi-static compression load. All kind has three types of specimens referred to as level one, level two and level three. These tested models have been fabricated and tested under the same conditions.

2. Manufacturing of Profiles

The corrugated profile is manufactured using metallic dies, specifically iron. All the composite specimens have been manufactured by hand lay-up using E-glass fabric, epoxy resin. The specification of the material used are given in Table (1) the specimens were fabricated by placing the woven roving fiberglass in the fabrication model as layers on each other. The woven roving fiber is passed through a resin bath, causing resin impregnation. The fabricated specimens were cured at room temperature for 24 hrs to provide good hardness and shrinkage. Then the cured specimens were extracted from the fabrication model to prepare them for the crushing test.

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Table 1. Types of materials used for constituents' fabrication of specimens by hand lay-up

Epoxy Resin	UK Epoxy Resins UKH 137 Epoxy
Hardener	UK Epoxy Resins UKH 136 Hardener
Woven roving E-glass fiber	Synthetic fiber: 500 g/m^2
No. of layers of each specimens	Four layers

Figure (1.a) shows the three metallic dies used for the fabrication of corrugated composite specimens using the hand layup process and some of the tested specimens are shown in Figure (1.b, c, and d).

a
b
c
d

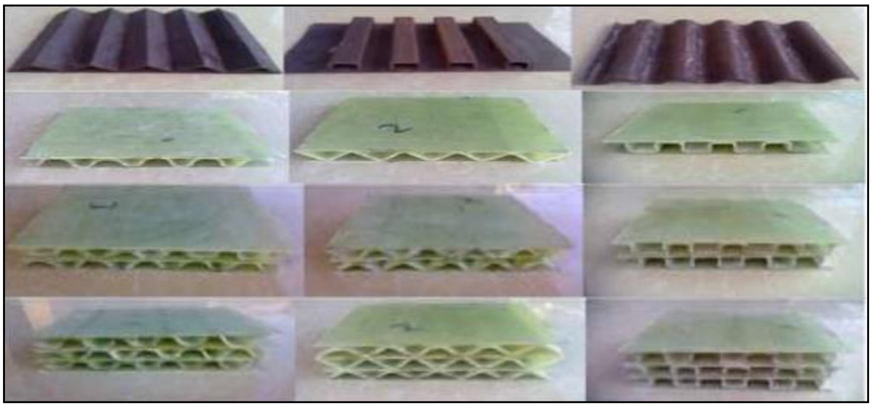

Figure 1. a) Different metallic dies used for specimen's fabrication; b) Square specimens; c) Sinusoidal specimens; and d) Triangular specimens

2.1. Crashworthiness Performance

The important factors which are used as a measure of the efficiency of performance of energy absorbers and their selection criteria are discussed in detail by Ezra and Fay (1987). Crashworthiness performance parameters are useful in comparing different composite materials and structures. A typical load-displacement curve of composite shells with the main parameters and the main regions are illustrated in Figure (2).

The main findings from the load-displacement curves are the main stages of the crushing response: pre-crush, post crush, and compaction stage.

2.1.1. Energy absorption (EA)

It represents the absorbed energy during compression. It is defined as the area under the force-displacement curve and expressed as follows:

$$EA(d) = \int_0^d F(x)dx \quad \text{..... (1)}$$

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where $F(x)$is the instantaneous force, and d is the displacement of the impactor.

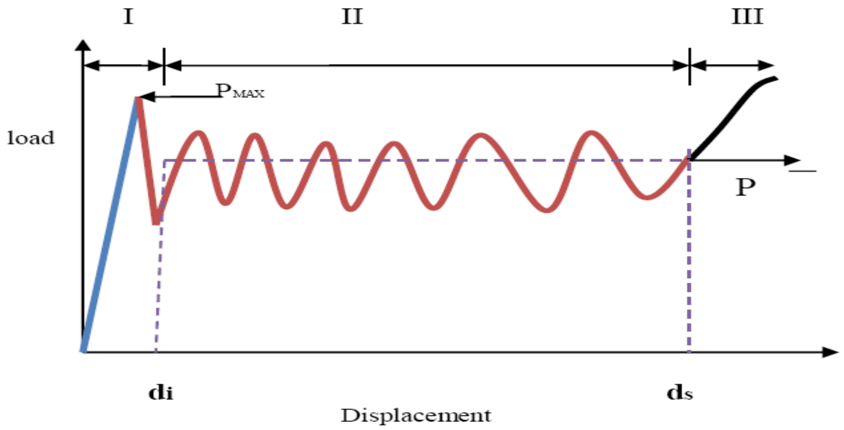

Figure 2. Typical load-displacement curve of a corrugated composite with its main parameters

2.1.2. Specific energy absorption (SEA)

It is the energy absorbed per unit mass. It is an indicator that balances energy absorption and mass for designing energy absorption structures. SEA is defined as (Hull, 1982 and 1983):

$$SEA(d) = \frac{EA(d)}{m} \quad \text{..... (2)}$$

where (m) is the total mass of a structure and EA is the total absorbed energy defined by Eqn. (1).

2.1.3. Crush Force Efficiency (CFE)

It is an indicator of the load uniformity of the structure. For crashworthiness structures, the high value of *CFE* is needed and it's expressed as follows:

$$CFE = \frac{MCF}{PCF}\% \quad \text{..... (3)}$$

where *PCF* represents the peak crush force in the force versus displacement curve under the axial impact. The mean crush force *MCF* can be obtained as:

$$MCF = \frac{EA}{d} \quad \text{..... (4)}$$

2.2. Experimental Test Set Up

The specimens were tested in quasi-static axial compression between two flat plates. ASTMD1621 standards, with a full-scale load range of 4000 kN were used. Three replicate tests were conducted for each type of model. All models were compressed at a rate of 2.5 mm/min until limited crush, which implies complete compaction of the tested specimen and loads records increases sharply is reached. Load and displacement were recorded by an automatic data acquisition system.

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3. Results and Discussion

This paper presents the results and discusses these results in detail through its articles. In this research, initially, comprehensive quasi-static crushing tests were performed to examine the influence of the design parameters (the specimens' geometry and corrugated profiles) on the energy absorption characteristics of composite plates. All specimens were fabricated manually using the hand-lay-up process. The material used for composite specimens is woven roving fiberglass and epoxy resin.

In this study, 27 specimens were made and tested under the same conditions. These types of specimens are divided into three levels. Level one has a single corrugated plate, level two has two plates, and level three has three corrugated plates. Each level has three different profiles: Sinusoidal, triangular, and square profiles. The specimens that recorded the highest value and the lowest value of the specific energy absorption will be explained.

Different parameters are used to measure the crashworthiness performance. The Crashworthiness Parameters, *CWPs*, used in this research are; specific energy absorption, E_{sp}. The measured crashworthiness parameter resulted were summarized in Table and plotted in a form of curves and diagrams as following;

3.1. Single Corrugated Composite Plate Fixed Between Flat Composite Plates with Triangular Profile

A Typical load-displacement curve for one triangular under quasi-static compression load is shown in Figure (3.a). As it can be seen curve, initially the load increases gradually with the increase in displacement up to initial failure where maximum load achieved 120 kN at displacement 13 mm. subsequently, load drops down till to 17.2 kN and displacement 21 mm. Farther that starts increasing gradually up to the final crushing load of the specimen as shown in the Figure (3.b) describes crushing stages of the specimen.

3.2. Two Corrugated Composite Plate Fixed between Flat Composite Plates with Square Profile

Figure (4.b) shows a typical crushing deformation of the square subjected to quasi-static compressive load. In this specimen, the plate resistance reaches its first and highest peak 89kN at a deformation of 10 mm. immediately after this stage start (plastic deformation), the load slows down until the compression is about 13kN at displacement 17 mm, after that increase resistance the loading until compression 82 kN at 31 mm, after that drops slowly until the compression 30 kN. On the other hand, the specimen load-carrying capacity decreases gradually with the progress of the crushing process. It is seen that the progressive folding in buckling is characterized by hinge formation and folding of the specimen as in the case of ductile fibre-reinforced materials with the development of wrinkles. These wrinkles and buckles initiate and develop sequentially from one end of a specimen under the buckling process. The accumulation of the materials of the specimen caused the growth in the load/displacement curve at the end is shown in Figure (4.a).

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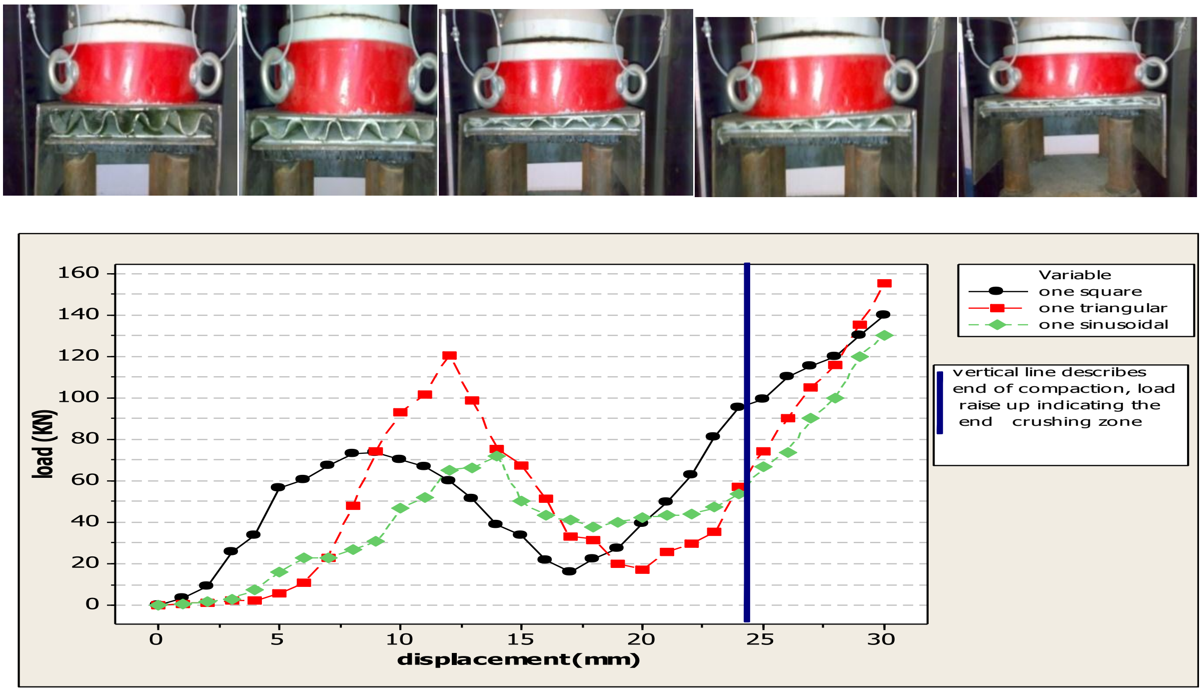

Figure 3. *a* and *b*) load-displacement curve and deformation history of level one of composite specimens

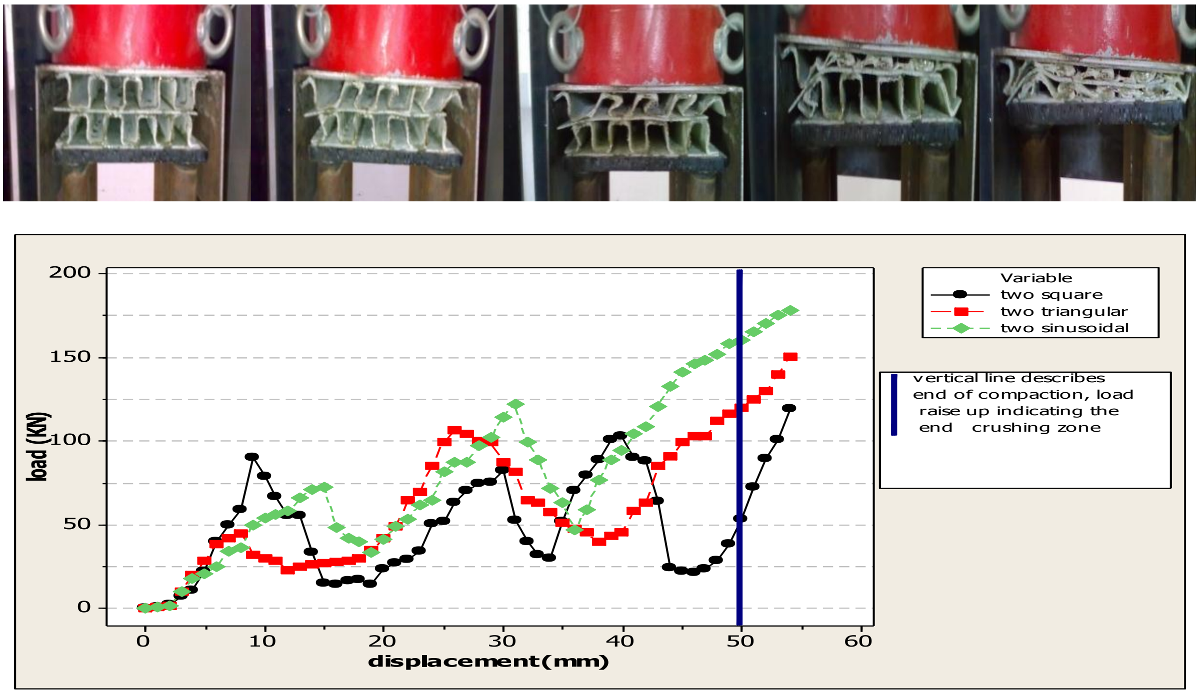

Figure 4. a and b) Three corrugated composite plate fixed between flat composite plates with sinusoidal profile

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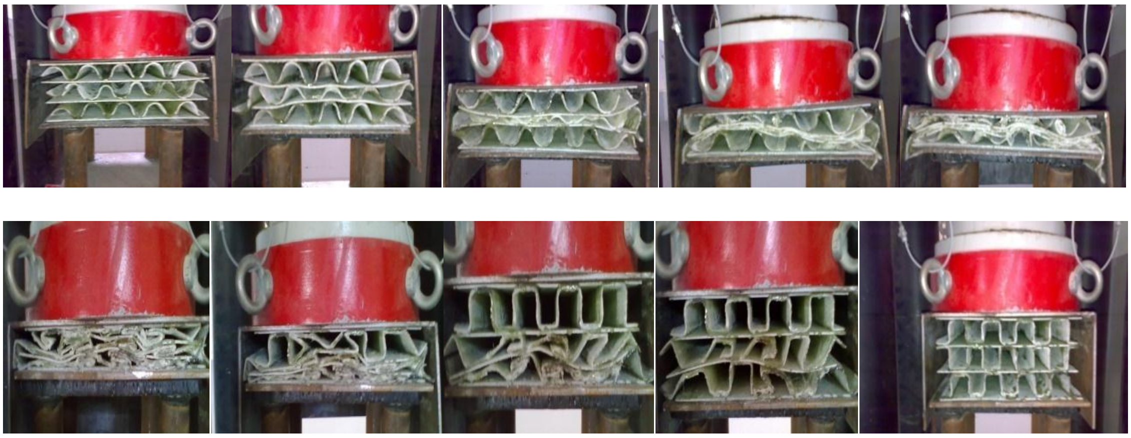
3.3. Three Corrugated Composite Plate Fixed between Flat Composite Plates with Sinusoidal Profile

In general, three sinusoidal specimens were crushed in the same manner as composed specimens except that no fracture occurred for three sinusoidal specimens. As shown in Figure (5.b), the crushing load increases until the compression is about 14mm when full resistance is developed with a 44 kN load. Immediately after this stage start (plastic deformation), the load slows down until the compression is about 18mm when full resistance is developed with 21 kN, after that increase resistance the loading until compression 92 kN at 33 mm, then drops slowly until the compression 74 kN. Then, after that start, the deformation increase slowly and decreases under the load until the compression is about 40mm, after that increase resistance of the loading until compression 103 kN at 46 mm. Subsequently, load drops down to 70 kN and displacement 49 mm when full resistance is developed with 100 kN. This behaviour seems to continue until complete crushing when the load increases sharply.



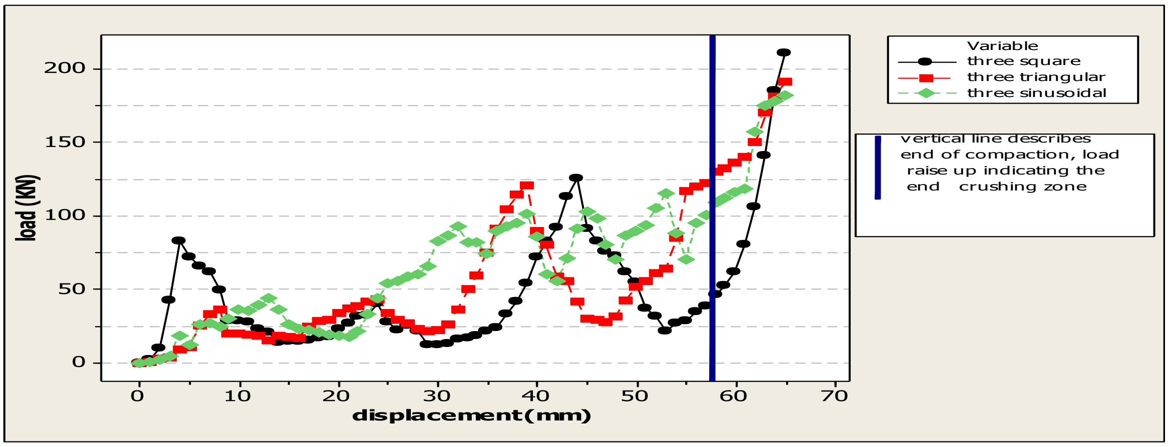


Figure 5. *a* and *b*) Load-displacement curve and deformation history of level three of composite specimens

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3.4. Three Corrugated Composite Plate Fixed between Flat Composite Plates with Square Profile

Typical load displacement curve obtained from progressive crushing of three square specimen is shown in Figure (5.b). Initially the load increased to a peak value 82 kN, 5 mm. immediately after this stage start (plastic deformation) the load slow down until the compression is about 15 mm when full resistance is developed with 13 kN, after that increase resistance the loading until compression 40 kN at 325 mm, after that droop slow until the compression 12 kN. Then after that start the deformation increase slowly and decrease under the load until the compression is about 45 mm. Subsequently, load drops down till to 21.5 kN and displacement 54 mm. Farther that starts increasing gradually up to the final crushing load of specimen as shown in Figure (5.a) describes crushing stages of specimen.

After completing all the lateral crushing tests the equations shown above are used in calculating the failure parameters of the lateral tests for all specimens, the results obtained from these tests can be seen in Table (2), and they are represented by the curve in Figure (6).

Table 2. Crashworthiness parameters of lateral tests for all specimens

The level	Sp-type	P_{max} (KN)	$\overline{P}$ (kN)	E_t (kJ)	W (kg)	E_{sp} (kJ/kg)	CFE* %	SE** %
One level	sinusoidal	72	41.32	0.413	1.030	0.401	57	73
	triangular	120	59.61	0.834	0.900	0.926	50	79
	square	73.6	45.97	0.689	0.770	0.895	62	74
Two level	sinusoidal	122	67.9	1.697	1.780	0.953	89	62
	triangular	106.6	52.09	1.823	1.550	1.176	50	67
	square	103	49.09	2.116	1.340	1.579	55	80
Three level	sinusoidal	115	64.09	2.884	2.530	1.139	67	60
	triangular	120	47.25	2.126	2.200	0.966	80	55
	square	125	47.62	2.762	1.910	1.446	58	64

(CFE) Crush Force Efficiency
***** (SE) Stroke Efficiency***

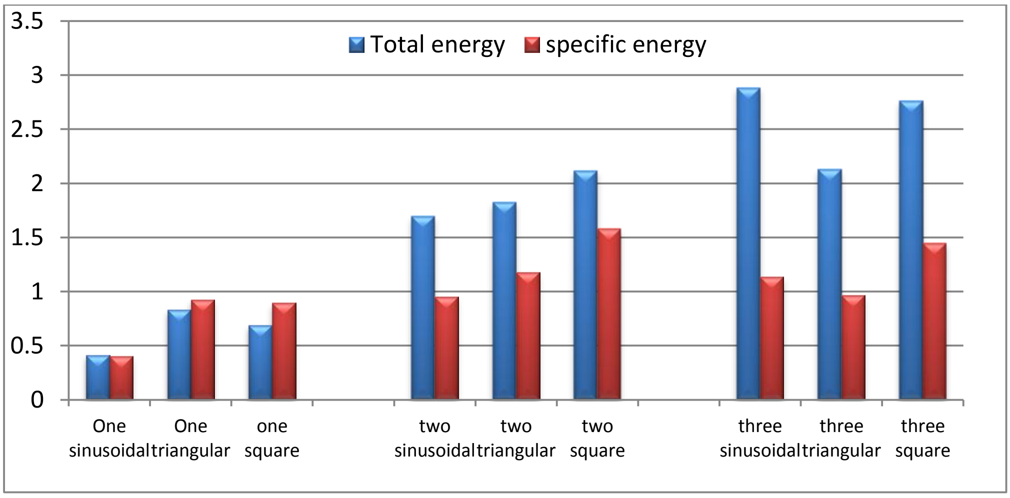

Figure 6. Total energy and specific energy of all specimens

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4. Conclusion

A series of composite plates with different corrugation profiles (sinusoidal, square, and triangular) with flat composite plates placed at the top and bottom of corrugated plates has been subjected to quasi-static compression load. The difference of the specimens' shapes offers a comparison between them in terms of the effect of the corrugation profile on energy absorption capability. Based on the results obtained, the main conclusion points can be summarized as follows;

- The specimen geometry has a considerable effect on energy absorption capability and load-carrying capacity.
- It has been observed that the change in corrugation profile has an important effect on energy absorption capability. It has been found that specimens of sinusoidal profile recorded the highest values of energy absorption capability comparing to specimens with a square and triangular profile.
- It has been observed that the specific energy absorption and load-carrying capacity increased with the increase of the number of corrugated plates. It has been found that the relationship between the two factors is directly proportional.
- The highest value of specific energy absorption of group A specimen has been recorded by two squares (1.579 kJ/kg). However, the three square specimens were second with (1.446 kJ/kg), and the specimen of one sinusoidal recorded the lowest value of (0.401 kJ/kg).

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