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Effect of Fiber Orientation Angle on the Energy Absorption Characteristics of Composite Tubes

Dr. Hussain J. Al-Akawi
Electromechanical Engineering Department, University of Technology/Baghdad
Email: Alalkawi 2007@yahoo.com
Dr. Mohammad Abdul Hassan Wheib
Training and Work Shops Center, University of Technology/ Baghdad
Dr. Sa'ed A. Shakir
Engineering College, University of AL- Mustansiriya /Baghdad
Olla Hussain Ali
Engineering College, University of AL- Mustansiriya /Baghdad

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ABSTRACT

The purpose of the paper is to present a study of the effect of the ply orientation angle on the crushing behavior, energy absorption, specific energy absorption, and failure mode of woven glass fiber/polyester laminated composite tube. Glass-polyester tubular specimens with circular cross-sectional geometry and (+45˚/-45˚, +60˚/-30˚, 0˚/90˚) fiber orientation angles were fabricated and crushed by quasi-static test under the same condition to examine the energy absorption characteristics and to calculate the crashworthiness parameters. The load-displacement curves of the tested tubes were presented and described; several failure modes of the crushed tubes were observed and discussed. It has been found that the fiber orientation angle has a considerable effect on the crushing characteristic of the collapsed tubes and the failure mode, and (0˚/90˚) fiber orientation angle tubes exhibit the highest SEA (specific energy absorption) 33.108 kJ/kg, crush force efficiency (0.7), crush strain relation (0.81) and a load/deformation curve closer to the ideal curve than the other specimens.

Keywords: Crushing, circular tube, Failure mode and Energy absorption

تأثير زاوية اتجاه ألألياف على خصائص امتصاص الطاقة لأنابيب المواد المركبة

الخلاصة

يهدف البحث الحالي إلى دراسة تأثير زاوية اتجاه الفايبر على سلوك التحطيم وامتصـــاص الطاقة والطاقة النوعية الممتصة وأسلوب الفشل لأنابيب مصنوعة من نســيج أليــاف الزجــاج والبولستر. تم تصنيع عينات أنبوبية من ألياف الزجاج والبولستر ذات مقطع دائري وتكون زاوية اتجاه الألياف (+45°/-45°، +60°/-30°،0°/90°) وسحقت بالاختبار الشبه استاتيكي وتحت نفس الظروف لفحص خصائص الطاقة الممتصة وكذلك لحساب متغيرات قابلية التحطيم لها. وقد رسمت منحنيات العلاقة بين الحمل والإزاحة للأنابيب التي اجري الاختبـــــار لهـــا وتمـــت

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

مناقشتها كما لوحظ عدة أنواع من أساليب الفشل للعينات التي اجري الاختبار لها وتمت مناقشتها. لقد وجد أن لزاوية اتجاه الفايبر تأثير مهم على خصائص التحطيم واسلوب الفشل للأنابيب التي تم تحطيمها. كما وجد أن الأنابيب ذات زاوية اتجاه الألياف (0°/90°) أعلى طاقة نوعية ممتصة (33¸108) كيلو جول/كغم، واعلى كفاءة قوة تحطيم (0¸7) واعلى علاقة انفعال التحطيم (0¸81) ويكون شكل منحني الحمل/ التشويه لها اقرب من شكل المنحني المثالي عن باقي العينات.

INTRODUCTION

Due to the superior strength-to-weight ratio and unmatched design and manufacturing flexibility, composite materials are becoming more popular by offering significant weight reduction and safety [1]. Hull [2] classified three modes of failure for square-ended brittle material tubes. These three modes were Euler buckling, which was easily avoided, shell buckling and progressive folding, and brittle fracture. The brittle fracture mode was then further categorized into catastrophic failure and progressive crushing, and progressive crushing was further categorized into splaying and fragmentation. Fragmentation was characterized by crushing and then breaking off of small pieces both inside and outside of the tube. Energy absorption capability of composite wrapped aluminum tubes was investigated by Shin et al [3] under axial compressive and bending load. The effect of ply orientation under these load condition was examined. It is concluded that the best energy absorption is attained in tubes wrapped with 90º ply orientation. Pham [4] presents a nonlinear finite-element analysis method to analyze a composite structure subjected to axial impact load. The analysis was performed using MSC/DYTRAN finite element code while pre and post processing were done using MSC/PATRAN program. A steel tube of the same geometry was analyzed for comparison purpose. It was found that the composite tube post-buckled collapsible length increases at a much faster rate than that of the steel tube. The composite tube shows a sinusoidal buckled mode shape, followed by sideways buckling. On the other hand, the thin walled steel tube undergoes progressive buckling displaying an accordion-folding pattern at the impacted end. Mamlis et al. [5] studied the crush behavior of carbon fiber-reinforced composite tubes. They explored the mechanisms of crushing and crash growth and identified three distinct modes of collapse: progressive end-crushing of the tube, starting at one end of the tested specimen— (Mode 1), (Mode II) which is a mode of collapse characterized by unstable local tube wall buckling on all four tube sides at one end of the tested square tube, and shell brittle failure associated with the formation of a circumferential crack and mid-length collapse mode (Mode III). The mode of collapse depends upon a number of factors related to the properties of the fibers and matrix and the arrangement of the fibers, as well as to the geometry of the shell of composite tubes. Gning et al [6] presented experimental results obtained from quasi-static and impact indentation tests on thick ±55º filament wound glass/epoxy tube. It is found that the damage in static indentation is similar to that noted in impact tests but the damage dimensions are not identical. Zeng et al. [7] simulated the crash behavior and energy absorption characteristics of 3D braided composite tube subjected to axial impact loading, using the explicit finite element Code LS-

DYNA. The effect of geometrical and braid parameters on the energy absorption characteristics were investigated. Han et al. [8] carried out a numerical investigation to evaluate the response and energy absorbing capacity of hybrid composite tubes made of unidirectional pultruded tube over wrapped with ±45˚ braided fiber reinforced plastic (FRP). The numerical simulation characterized the crushing behaviors of these tubes subject to both quasi-static compression and axial dynamic impact loadings. Two types of braided FRP, glass and carbon fibers, were considered. Parametric studies were also conducted to examine the influence of the tube's length, thickness and type of braid, as well as the loading conditions on the crushing behavior of the tubes. It was found that braiding over wraps could be used to effectively enhance the crushing characteristic and energy absorbing capability of the tubes. Mahdi et al [9] deals with the implementation of artificial neural networks ANN (Artificial neural networks) technique in the prediction of the crushing behavior and energy absorption characteristics of laterally loaded glass fiber/epoxy composite elliptical tubes. Aljibori [10] this research study the effect of the number of layers (tube thickness) on the crushing behavior, energy absorption, specific energy absorption, and failure mode of woven roving glass fiber/epoxy laminated composite tube. Aljibori [11] studied the energy absorption capacity of composite tubes fabricated from high tow count filament glass fiber with different number of layers. Glass-epoxy tubular specimens with circular cross-sectional geometry and 0/90° fibers orientation angle were fabricated and crushed by quasi-static test to examine the energy absorption characteristics and to calculate the crashworthiness parameters. It was found that the number of layers and fiber orientation angle had a significant effect on the energy absorption capability.

Experimental investigation of the effect of different ply orientation angles on energy absorption capability of composite tubes presented in the present work. Three different types (0˚/90˚,+60˚/-30˚, +45˚/-45˚) fiber orientation angle tubes were fabricated and subjected to an axial compression load. The failure mode and the main crushing parameter were investigated.

EXPERIMENTAL WORK

Materials and Specimens

Three types of tubular specimens have been investigated, with circular cross section and different fiber orientation angles (0˚/90˚,+60˚/-30˚,+45˚/-45˚). The materials used are woven roving glass fiber and polyester resin. All specimens fabricated in the same way under the same conditions with fixed fiber orientation angles. The outer diameter, length and thickness for the tubes are fixed to 50, 100 and 1.5 mm respectively for all the specimens as shown in figure (1).

Fabrication Process

The principle of hand lay-up process was used for the fabrication process. However, there is a difference in the details of fabrication for each type due to the difference of ply orientation angles. The First step in the manufacturing process was to prepare Woven glass fiber by cutting (0°/90°) woven fiber glass at (0°, 45°,60°) angles with length (450)mm and width (300)mm to get the required fiber orientation angles. The second step was to coat the circular mandrel with a thin layer of a special wax named (Carnauba Wax) supplied by U.S.A factories (meguiarś). A(100) gram of liquid resin was mixed with (2)g catalyst, according to the supplied instructions, both were blended by hand at room temperature until there was a uniform and complete mixing of components. After that a thin layer of resin was applied to the mandrel by using brush, and a layer of woven roving fiber glass was rolled onto the solid aluminum mandrel of a circular section. Then another thin layer of resin was applied to the first layer and the second layer of woven roving glass fiber was rolled onto the first layer. In order to compact and to consolidate the surface of the tube, and applied an equal pressure on the fiber impregnated by the resin a mold was designed and fabricated from aluminum stock. The tube was cured at room temperature for (24) hours, then it was removed from the mandrel and left for seven days. The ends of the tube were irregular so they were cut off with a diamond cutting tool. Turing machine was used in preparation of the specimens figure (2), in order to insure flat smoothed – end surfaces, parallel to each other and at right angles to the length of the specimens so as to prevent localized end failures. The specimens were then weighed and measured for all of the relevant dimensions. The fiber volume fraction was fixed to (40 %) for all the specimens.

Quasi-static Compression Tests

Before the mechanical tests, all specimens diameter were measured, using a micrometer, at three equidistant points around the perimeter of each tube at three points along the specimen length, and the length was measured in four points. Crush tests were carried out on MICROCOMPUTER CONTROLLED ELECTRONIC UNIVERSAL testing machine model (WDW_50E) shown in figure (3) with full scale load range of 50 KN. The specimens were placed in vertical alignment between two horizontal platen in the test frame. The specimens were then quasi-statically loaded under axial compression at (10) mm/min which implies a complete compaction of tested specimen. Load and displacement measurements were recorded during each test and results were stored electronically in ASCII-format data files. Crushing progress of specimens shown in figures (4, 6,8).

RESULTS AND DISCUSSION

Failure Modes

The collapse modes for composite tubes under crushing load varied with the fiber orientation angles. Three different failure modes were observed experimentally during the crushing of the tubes.

The 0°/90° ply fiber orientation angle tubes were crushed progressively from one end by splaying mode as shown in figure (4). Which is a type of stable brittle fracture in accordance with the classification mode by Hull [2]. In each crush test the fibers have splayed in a series of fronds to the outside and inside of the tube, and a crack has formed along center of the wall of the tube, with a debris wedge of pulverized material just above the main intra wall crack due to local fiber and matrix crushing of the bent lamina bundles against the cross-head of the testing machine, as shown in figure (5).

The +45°/-45° ply fiber orientation angle tube failed by progressive folding instead of fracturing and splaying as observed in the previous case which is shown in figure (6), a local buckling mode indentified by Farley [12] similar to the accordion was observed. The tube wall buckled outwards, with progressive increases in diameter till the first flattening outward fold is fully developed. Then the second fold, which is the first inward fold, starts to develop with the reduction in diameter. The deformation continuous with the formation of the subsequent outward and inward folds. The deformation of the tube was observed after buckling is also shown in the figure (7).

The +60°/-30° ply fiber orientation angle tubes failed by irregular collapse mode observed by Hamouda et.al [13], figure (8) shows the deformation process of the +60°/-30° fiber orientation tubes. It can be seen that the tubes first collapsed from the top end propressively then unstable intra-laminar crack growth caused the delamination of wall layers finally the tube buckled and became unstable between the compression plates of the tester. Figure (9) shows the final deformation of the tube.

Load-Deformation Curves

An ideal energy absorber has a force- deflection curve with a square-wave profile; as shown in figure (10) crushing occurs at a constant force until the energy absorber is completely consumed, thus maximizing the absorption energy [14]. The load-deformation curves for tubes with different ply orientation angle are shown in figure (11). Among them the 0°/90° tube exhibits the highest crush load throughout the crushing process, and by contrast the +60°/-30° and +45°/-45°. By examining the curves carefully, it is noted that the tubes crushed with the different failure mode as described in the previous section. For 0°/90° load-displacement curve, the load starts increasing recording value of (16.62 KN) at displacement of (3.1735 mm) as shown in figure (11), the specimens started with micro-cracking and matrix cracking causing a sharp drop occur in the load-displacement curve. Consequently, load increases during this crushing stage followed by slight fluctuation then it remains almost constant around this value. The 0°/90 tube has load-displacement which approximates the ideal profile.

In the +45°/-45° load-displacement curve it is observed an increasing of load up to (6.94 KN) at (3.2255 mm), followed by a lower stable crushing load where progressive failure initiates. Subsequently, at the last stage the load rises up rabidly due to end of crushing zone.

For +60°/-30° load-displacement curve, the axial load increased initially recording value of (6.92 KN) at (4.6015 mm). Then the curve being fluctuated up and down due to multi-failures in the specimen, followed by rapid decrease in the load due to instability of the tube. Table (1) listed the crushing loads and displacements for all the tubes.

Crushing energy absorption

The energy absorbing capability can be estimated by knowing different parameters. These parameters are illustrated in table (2) and explained in following sections.

Total Energy Absorbed (TEA)

The absorbed energy during the crushing of a specimen is given by the area under the load/displacements curve, which is a function of specimen cross-sectional area and material density. This energy can be obtained by numerical integration of the load displacement curve [15]. From the series of experiments performed, it is found that 0°/90° subjected to axial compressive load has the maximum total energy absorption (993.46J), while the +45°/-45°exhibits the minimum value of total energy absorption (340.93J). Aljibori [11] found that the (TEA) for filament glass fiber /epoxy composite tube was (0.78 kJ).

Crush Force Efficiency (CFE)

CFE is the ratio between average crush load and maximum crush failure load which is used to characterize the shape of the trace. It is useful to measure the performance of an absorber. It can be calculated as [10] CFE = P_{av} / P_{max} where P_{max} and P_{av} are the maximum and the average crushing load, respectively. In some cases of composite crushing, after maximum load of crushing was achieved, the crushing load falls down followed by rising up of crushing load resulting in obtaining an overall average crushing load greater than the maximum initial load of crushing. Consequently, crushing force efficiency will be more than one. For the series of conducted experiments, no cases were recorded. All the specimens exhibit an average crushing load less than the maximum crushing load. The results of crush force efficiency shows that the maximum value produced by 0°/90° (0.70 kN/kN). Aljibori [11] found that the (CFE) was (0.6 kN/kN).

Specific Energy Absorption (SEA)

The most important parameter that was determined from each crush test was the specific energy absorption (SEA), which is used to compare different materials or different geometry of specimens. The specific energy absorption is defined as the amount of energy absorbed per unite mass of crushed material [16] SEA = P_m (L/M), where P_m is the mean crush load, M is the mass and L is the length of the specimens. Since tested specimens are different from each other with respect to their ply orientation angles, (SEA) was found the suitable parameter to compare between the three structures. 0°/90° exhibits maximum specific energy absorption (33.108 KJ/Kg), followed by +60°/-30° (11.744 KJ/Kg) and +45°/-45° which came in the last (11.515 KJ/Kg). Aljibori [11] found that the (SEA) was (7.75 kJ/kg), the tested tube was glass fiber/epoxy with 100 mm diameter and 100 mm height, which is failed by irregular mode.

Volumetric Energy Absorption (VEA)

The Volumetric Energy Absorption (VEA) in an essential parameter for the energy absorbing system design. The VEA is the ratio between the total energy absorption to the volume of the specimen. The SI unit is kJ/m^3 and VEA can be obtained from the equation [10]: VEA = TEA / V Where TEA are the total energy absorption and V is the volume of the specimens. The VEA increases gradually with increasing the ply orientation angles. This is because the volumes of the specimens are equal. Thus, the amount of VEA will depend on the TEA, since 0°/90° produced the highest TEA then the VEA of 0°/90° will be the highest (5729.296 KJ/m^3) and the lowest one is +45°/-45°(1966.147 KJ/m^3).

Crush Strain Relation (C)

The crushing strain relation (C) allows a homogeneous comparison of the structural response independently from the material elastic properties. The higher the value of the C parameter, the higher the magnitude of energy absorbed by the structure and the more optimum the design of the structure. Crushing strain relation is the ratio between the crushing lengths to the total length of the specimens [11]: ($C = (D_f\text{-}D_i) / H$), Where ($D_f\text{-}D_i$) are the final and the beginning of the crushing distance respectively, and H is the height of the specimens. The highest (CS) was (0.81) for 0°/90° fiber orientation tube and the lowest CS was produced by +60°/-30°. For four layer 0°/90°filament fiber glass/epoxy tubes manufactured filament winding process Aljibori [11] find that the CS was (0.71mm/mm).

Load Ratio (LR)

The load ratio parameter is very important to study the failure modes along the crushing failure and the load ratio (LR) is the ratio between the initial failure load P_i and the maximum failure load P_{max} and this can be shown as [11] $LR = P_i / P_{max}$, when the initial failure load P_i is the same value of the maximum failure load thatś mean the load ratio will equal to 1 and this means that the structure initially crushed in a limited catastrophic failure mode. In addition, if the load ratio LR is the less than 1, that is mean a matrix failure mode will observed in the initial crushing stage of the specimen. +60°/-30° shows the lowest value of LR of 0.77 and the other specimens have the same value which is 1 as shown in table (2). Aljibori [11] find that the (LR) was (0.87 kN/kN), since the tube failed initially at a midpoint then failed by irregular mode.

CONCLUSIONS

1- The (0°/90°) fiber orientation angle tubes fails by splaying mode, (+45°/-45°) tubes fails by progressive folding mode and (+60°/-30°) tubes fails by irregular collapse mode.

2- The load/displacement curve for (0°/90°) fiber orientation angle tubes is closer to the ideal curve than (+60°/-30°) and (+45°/-45°) tubes.

3- The (0°/90°) fiber orientation angle tubes exhibit the highest SEA then (+60°/-30°) tubes and (+45°/-45°)tubes are the lowest.

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Table (1): crush load, energy absorbed capacity and specific energy absorption composite tubes with different ply orientation angles.

Ply orientation (degree)	Initial Load Pi (KN)	Maximum load P_{max} (KN)	Average load P_{av} (KN)	Initial Displacement Di (mm)	Final Displacement Df (mm)
2 layers (0°/90°)	16.62	16.62	11.69	3.1735	84.967
2 layers (+45°/-45°)	6.94	6.94	3.96	3.2255	83.848
2 layers (+60°/-30°)	6.29	8.14	4.14	4.6015	83.655

Table (2): Crashworthiness Parameters of Specimens

Specimens	TEA (J)	SEA (J/Kg)	VEA (KJ/m^3)	CFE (KN/KN)	C (mm/mm)	LR (kN/kN)
2 layers (0°/90°)	993.46	33108.617	5729.296	0.70	0.81	1.00
2 layers (+45°/-45°)	340.93	11515.287	1966.147	0.57	0.80	1.00
2 layers (+60°/-30°)	346.92	11744.640	2000.692	0.51	0.79	0.77

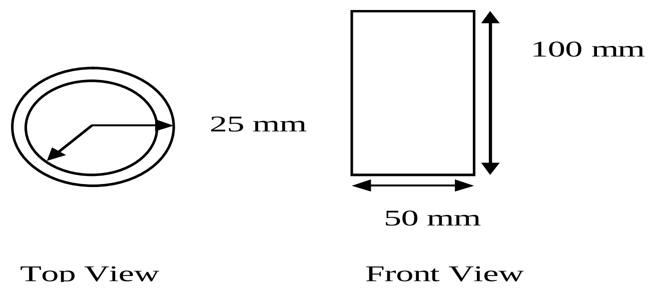

Figure (1): Top and front view of a specimen.

Figure (2): Turning machine used in specimens preparation.

Figure (3): The microcomputer controlled electronic Universal testing machine model (WDW_50E).

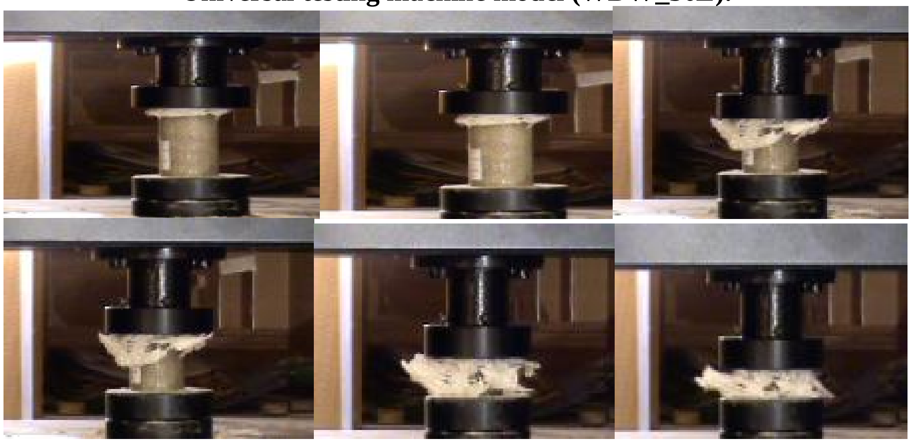

Figure (4): The process of crushing test of 0°/90° specimen.

Figure (5): Splaying mode.

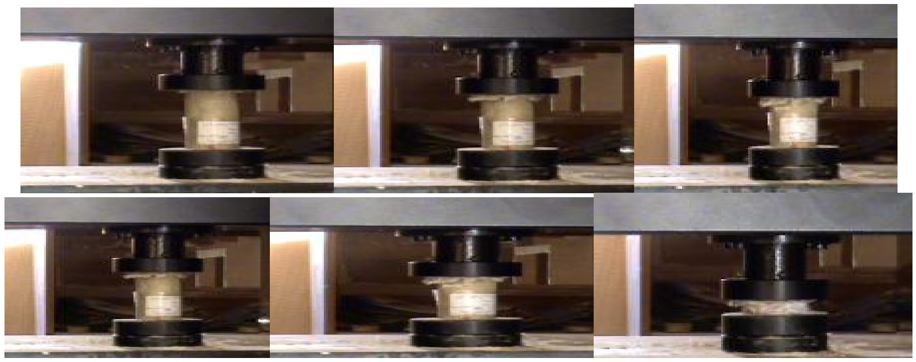

Figure (6): The process of crushing test of +45°/-45° specimen.

Figure (7): Folding mode.

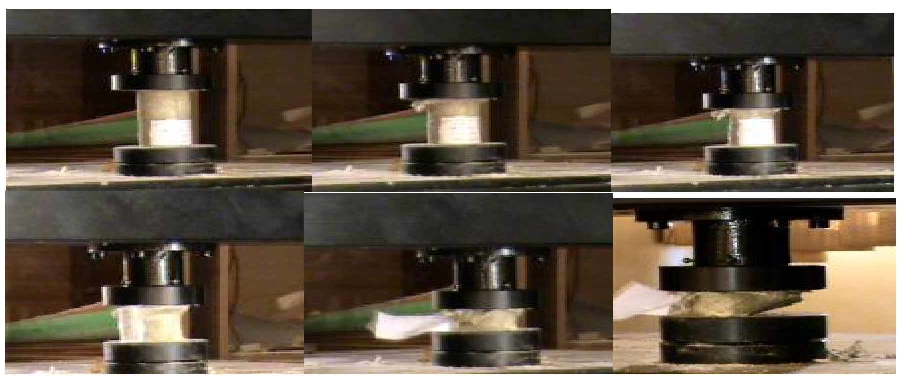

Figure (8): The process of crushing test of +60°/-30° specimen.

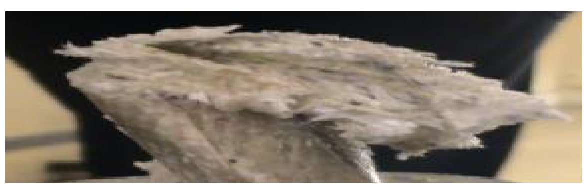

Figure (9): Final deformation of the +60°/-30° specimen.

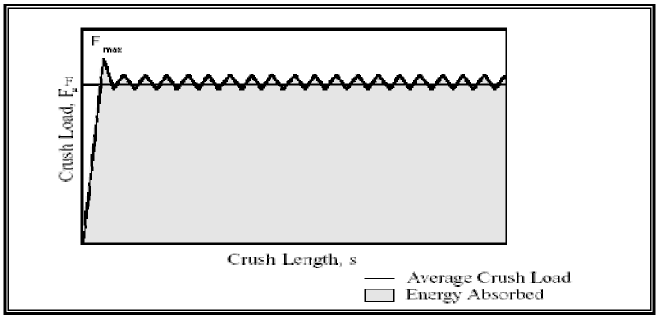

Figure (10): Ideal crush load vs. crush length

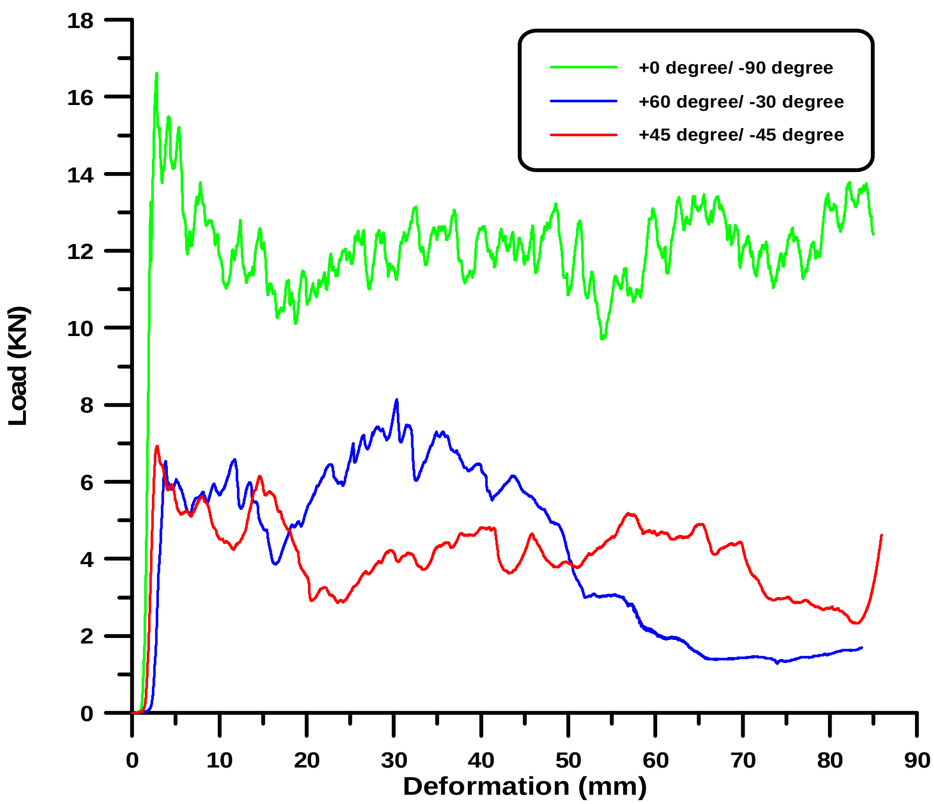

Figure (11): load-deformation curves.