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Structural Behavior of Timber Aluminum Composite Beams Under Impact Loads

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Abstract—An experimental along with numerical analysis has been carried out to investigate the behavior of simply supported timber aluminum composite beams under impact loads. The composite beams are made by connecting plywood slabs with aluminum beams (box sections) using adhesive epoxy material and mechanical fasteners (self tapping self drilling screws). The experimental program consists of testing a total of sixteen timber aluminum composite beams under impact loads applied by dropping constant weight from three different heights. The effects of several parameters are considered in the investigations. During the tests, the applied accelerations and midspan deflections are measured with time and impact forces are calculated for all the tested specimens. From the results of these tests, it has become clear how the impact characteristics of behavior of the tested timber aluminum composite beams are affected by the considered parameters in this study. A finite element dynamic analysis has been used for modeling and analyzing the tested composite beams. The adopted nonlinear finite element analysis through the use of ANSYS LS DYNA version 13.0 software gave compatible results with the experiment ones.

Index Terms— timber, plywood, aluminum, composite beams, impact loads, adhesive connection, ANSYS LS DYNA

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1 INTRODUCTION

During its service life and also at the time of its construction, a structure may be subjected to several types of static and dynamic loads. The one among these loads at which very limited amount of investigations are done is the impact loading, which can be expected to occur during manufacturing, service, and maintenance operations of a structure. An example of in service impact occurs during the manufacturing process or during maintenance; heavy tools can be dropped on the structure.

The response of the structure due to impact loading depends on the striker mass, its velocity and the relative rigidities of the projectile and the structure. Where the structure is very rigid, the striker undergoes extensive deformation and almost the entire kinetic energy is being transformed as deformations in the projectile. This impact is termed as 'soft impact'. Whereas, if the striker is very rigid, the energy of the striker is to a larger extent absorbed by the deformation in the structure and the process is termed as 'Hard Impact' [1]. The main characteristics of impact load are a high loading rate and a very short period of application that results in high material strain rates. Meanwhile, the mechanical behavior of structural materials can be changed due to high strain rates too. So, traditional static analysis methods cannot be used as a solution to this complex case. This subject has been paid attention to by many engineers [2].

The impact response of a structure can be divided into several categories. In the first, the entire energy of the impact is absorbed by the structure in elastic deformation, and then released when the structure returns to its original position or shape. Higher energy levels may exceed the ability of the structure to absorb the energy elastically. The next level is plastic deformation, in which some of the energy is absorbed by elastic deformation, while the remainder of the energy is absorbed through permanent plastic deformation of the structure. Higher energy levels result in energy absorbed through damage to the structure. Finally, the impact energy levels can exceed the capabilities of the structure, leading to catastrophic failure. The maximum energy which can be absorbed in elastic deformation depends on the stiffness of the materials and the geometry of the structure.

Composite structures are more susceptible to impact damage than a similar metallic structure. In composite structures, impacts create internal damage that often cannot be detected by visual inspection. This internal damage can cause severe reductions in strength and can grow under load. Therefore, the effects of foreign object impacts on composite structures must be understood, and proper measures should be taken in the design process to account for these expected events [3].

The importance of the effect of such type of loading on composite structures necessitates the study of the effect of impact loading on new configurations of composite structure. In the present work, the structural behavior of composite beams consists of plywood panels, which is one of the Engineering Wood Products (EWPs), as slabs, and

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aluminum box sections as beams investigated under the effect of dropping weight impact loads. The proper properties of timber, especially the EWPs, and aluminum in addition to composite action benefits give a chance that the two materials respective advantages can be utilized to the fullest extent.

2 EXPERIMENTAL ANALYSIS

2.1 Materials

The mechanical properties of the materials used in this investigation including structural aluminum alloy box section, plywood sheet panels, and thixotropic epoxy resin adhesive (Sikadur-31), were determined experimentally according to the American Society for Testing and Materials Standards (ASTM standards) [4,5,6,7,8]. The final results of these tests are summarized in Tables (1), (2), and (3).

TABLE 1
MECHANICAL PROPERTIES OF ALUMINUM ALLOY

Density (kg/m^3)	Yield Stress (MPa)	Ultimate Stress (MPa)	Modulus of Elasticity (GPa)	Tangent Modulus (MPa)
2685	191.84	236.32	67.67	1058

TABLE 2
MECHANICAL PROPERTIES OF PLYWOOD

Item	Plywood Face Grain Direction	Value	Unit
Ultimate Compressive Strength	Parallel to Applied Load	18.03	MPa
	Perpendicular to Applied Load	13.69	
Ultimate Tensile Strength	Parallel to Applied Load	13.27	
	Perpendicular to Applied Load	9.39	
Ultimate Flexural Strength	Parallel to Span	34.77	
	Perpendicular to Span	25.19	
Modulus of Elasticity	Parallel to Span	7357.6	
	Perpendicular to Span	4871.8	
Shear Modulus	--------------------	662.9	
Density	--------------------	450	kg/m^3

TABLE 3
MECHANICAL PROPERTIES OF SIKADUR-31 EPOXY RESIN

Compressive Strength (MPa)	Tensile Strength (MPa)	Flexural Strength (MPa)	Modulus of Elasticity (MPa)
35.0	25.0	40.0	4600

2.2 Fabrication of Specimens

The fabrication of the tested composite beams was done in two stages. In the first stage, the plywood slabs of the specimens were prepared by cutting them out of the available standard plywood panels. The dimensions of these slabs were (1200×300×18mm) and (2400×300× 18mm) taking into account that the direction of face grains of some of them was parallel to, and the others perpendicular to, the direction of the span length. In order to provide plywood slabs with thickness of (37mm), two plywood pieces were connected together by epoxy adhesive layer (Sikadur 31) of (1mm) thickness, pressed together by steel clamps from both sides and left for about three days for the epoxy hardening.

In the second stage, the two components (plywood slab and the aluminum beam) of the composite beams were connected together by epoxy adhesive layer (Sikadur 31) of 3mm thickness, pressed together by steel clamps from both sides, and left for about three days for the epoxy hardening. Finally, a self drilling self tapping screws, having 6mm diameter, were driven along the overall length of the beam specimens with 150mm spacing.

The intended use of adhesive epoxy material with the mechanical fasteners is firstly to provide full interaction between the components of the composite beams and secondly to increase the spacing between the mechanical fasteners, which may reach (30 mm) for these composite beams to satisfy full interaction without epoxy material. Using the adhesive epoxy material and mechanical fasteners also prevent the concentration of stresses and local damage that may be developed in the aluminum beams or the plywood slabs.

2.3 Dimensions of Specimens

The timber – aluminum composite beams were of (1.2m) and (2.4m) overall length and consisted of timber (plywood) slab of (0.018m) and (0.037m) thickness and (0.3m) breadth. A box section aluminum beam with (0.1m) depth, (0.05m) width, (0.004m) wall thickness, and a weight equal to (3.0 kg/m) was used. Typical composite beam sections are shown in Fig. (1).

The main variables considered in this investigation were the thickness of the plywood slab, the orientation with respect to the span direction of the face grain of the plywood slab, the span length, as well as the type of bending moment (sagging and hogging bending moments).

Twenty specimens of the composite beams, which divided into six groups, and six specimens of aluminum beams, which divided into two groups, were tested in this program.

One specimen from each group was tested statically, by applying a midspan line load, in order to investigate the static behavior of the conducted composite beams and their ultimate strength. The other specimens were tested under the action of impact loads. The full details of tested groups of the aluminum beams and composite beams are summarized in Tables (4) and (5), respectively.

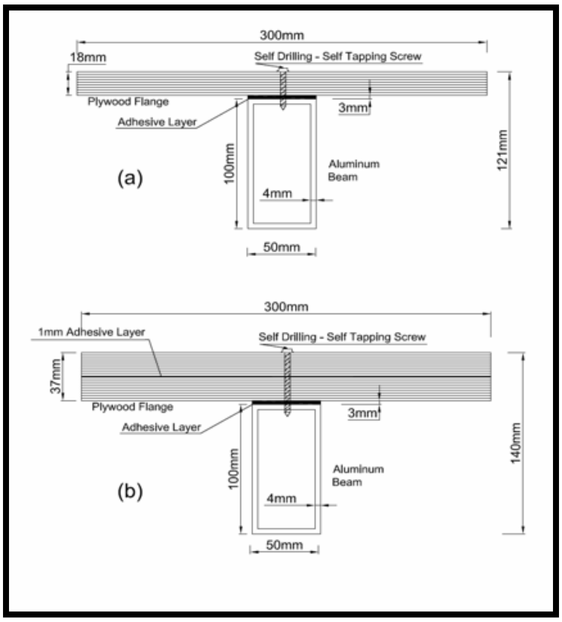

Figure 1 Typical Cross Section of Timber - Aluminum Composite Beams (a) one layer plywood flange , (b) two layers plywood flange

TABLE 4

DETAILS OF TESTED ALUMINUM BEAMS

Group No.	Designation	Weight (Kg/m)	Full depth (mm)	Flange width, mm	Flange thickness (mm)	Web thickness (mm)	Cross Sectional Area (mm^2)	Calculated Moment of Inertia (mm^4)	Overall length (m)
1	DA1	3.05	100	50	4	4	1136	1441259	1.2
2	DA2								2.4

2.4 Impact Test of Specimens

Impact loading tests were carried out by using the apparatus shown in Plate (1), where a constant weight (striker) was dropped on the tested specimens. The dropping weight is a solid steel cylinder having a mass of (30.83kg) with dimensions of (500mm) in length and (100mm) in diameter.

In all impact tests, the striker (dropping weight) was unrestrained vertically so that after the first impact it rebounded and then fell to impact the specimen again. The response of the composite beam specimens and their deformations could thus further develop under subsequent strikes. The response of the specimen under these strikes was, however, not as significant as under the first impact. In the present study only the behavior of the tested beam specimens under the first impact is examined by considering the time variation of the applied accelerations and the response of the tested beams from the start of impact to a duration of (0.25 - 0.50 sec) of the impact event.

TABLE 5

DETAILS OF TIMBER - ALUMINUM COMPOSITE BEAMS

Group No.	Designation	Plywood Flange Dimensions (mm)		Orientation of Plywood Face Grain to Span Direction	Beam Overall Length (m)	Beam Overall Depth (mm)	Region of Bending Moment
		Width	Depth				
1	D1Pr1S	300	18	Parallel	1.2	121	Sagging
2	D1Pn1S		18	Perpendi-cular	1.2	121	
3	D2Pr1S		18	Parallel	2.4	121	
	D2Pr2S		37	Parallel	2.4	140	
5	D2Pr1H		18	Parallel	2.4	121	Hogging
6	D2Pr2H		37	Parallel	2.4	140	

Plate 1 Impact Load Test Apparatus

Measurements were recorded for the specimens under each drop of the striker. An accelerometer was mounted to the top of the striker to provide an acceleration time history during the impact event. It was also used to estimate the impact load that the specimens were subjected to. A laser displacement sensor was provided at the midspan of the specimens in order to measure the midspan deflection time history of the tested specimens during the impact event. Single fall test was conducted for each test specimen. Different heights are used to fall the striker on the different tested beams, as shown in Table (6).

TABLE 6

LOADING CONDITIONS FOR IMPACT TESTS

Specimen's No.	Group Designation	Height of Dropping Weight (cm)
1	DA1	22
2		88
3	D1Pr1S	22
4		44
5		88
6	D1Pn1S	22
7		44
8		88
9	DA2	22
10		88
11	D2Pr1S	22
12		44
13		88
14	D2Pr2S	22
15		44
16		88
17	D2Pr1H	22
18	D2Pr2H	22

3 NUMERICAL ANALYSIS

Three dimensional nonlinear finite element modeling is used to investigate numerically the behavior of timber-aluminum composite beams that were tested experimentally under the effect of impact loading. The software ANSYS LS DYNA version 13.0 is used in the analysis.

The composite beams are modeled as to compose of two main components, aluminum beam and plywood slab, with full interaction between them. The modeling of plywood slab is developed by using SOLID164 three dimensional structural hexahedron element. The element is defined by eight nodes having nine degrees of freedom at each node: three translations, three velocities, and three accelerations. The aluminum beam was modeled by using SHELL163 three dimensional four nodes structural thin shell element. SHELL163 has 12 degrees of freedom at each node three translations, three velocities and three accelerations, and three rotations about the nodal axes. On the other hand, the dropping weight is modeled by SOLID164 three dimensional tetrahedral element, in order to achieve the cylindrical shape of the drop weight.

The nonlinear material properties of the aluminum beam are approximated, using the experimental results of tensile test of used aluminum alloy, by assuming a bilinear relationship for its uniaxial stress-strain relation and using the data shown in Table (1).

According to the way of fabrication and manufacturing of plywood, all of the specifications and standards focused on the properties of the plywood in the direction parallel and perpendicular to the face grains. Therefore, and depending on the experimental results data, the plywood was represented as elastic material with transverse isotropy in place of the orthotropic nature of its natural material by assuming identical properties in radial and tangential directions [9] and using the data shown in Table (2).

Finally, the material model adopted for the dropping weight is the rigid body material model. The use of rigid body material have advantages in reducing the solution time and ensuring that there are no deformations, which may develop in the drop weight during the impact [10].

4 RESULTS AND DISCUSSION

4.1 Experimental Results

4.1.1 Impact Force

All the specimens tested under impact loads did not fail, although they do undergo some permanent deformations during the tests. This was because that the larger impact load applied on the specimens of each group did not exceed about 50-60% of the ultimate static strength of these specimens, as summarized in Table (7).

The experimental time history of the impact force is derived from the recorded time history of the applied acceleration of the striker, which is measured, as previously explained, by an accelerometer attached to the striker during the impact tests of the beam specimens. The time histories of the applied impact forces for selected composite or aluminum beam with different heights of the dropping weight are shown in Figs. (2) to (5).

The global variations of the impact forces with time are approximately have the same behavior for all the tested composite beams and the aluminum beams, in which the maximum impact force stands up rapidly and goes down in no time. Subsequently impact force stands up again and decreases after several peaks until it vanishes.

TABLE 7

COMPARISON BETWEEN LARGER APPLIED IMPACT FORCE AND ULTIMATE STATIC STRENGTH OF TEST SPECIMENS

Group No.	Designation	Larger Applied Impact Force* (kN), F1	Ultimate Static Strength** (kN), F2	Ratio (F1 / F2)
1	DA1	17.60	30.12	0.584
2	D1Pr1S	22.32	37.08	0.602
3	D1Pn1S	20.22	35.51	0.569
4	DA2	6.36	12.75	0.499
5	D2Pr1S	8.73	17.36	0.503
6	D2Pr2S	11.70	23.94	0.489
7	D2Pr1H	8.13	16.69	0.487
8	D2Pr2H	10.54	21.43	0.492

* Larger applied impact force applied on the group's specimens
** Ultimate static load determined by static tests.

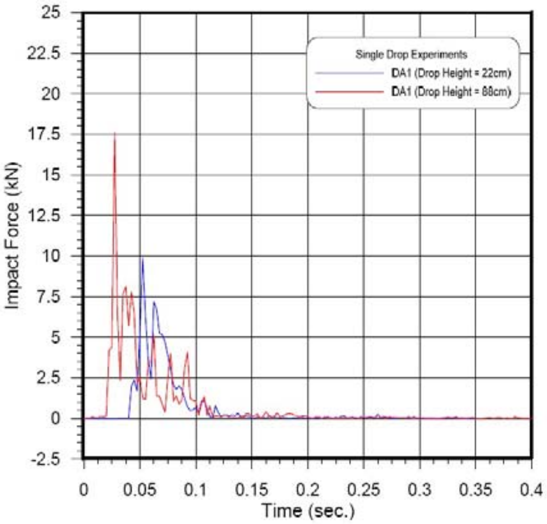

Figure 2 Impact Force Time History for Aluminum Beam (DA1)

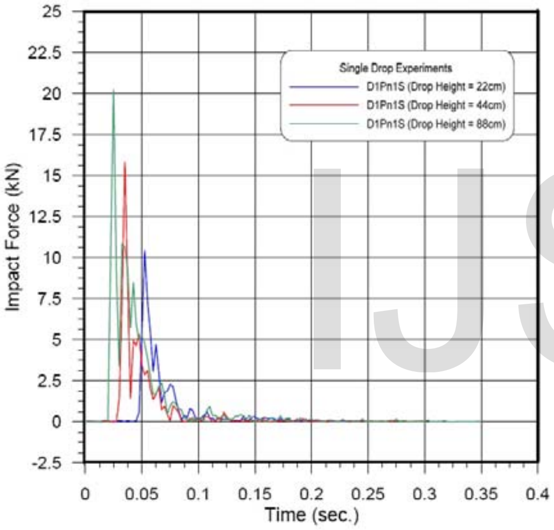

Figure 3 Impact Force Time History for Composite Beam (D1Pn1S)

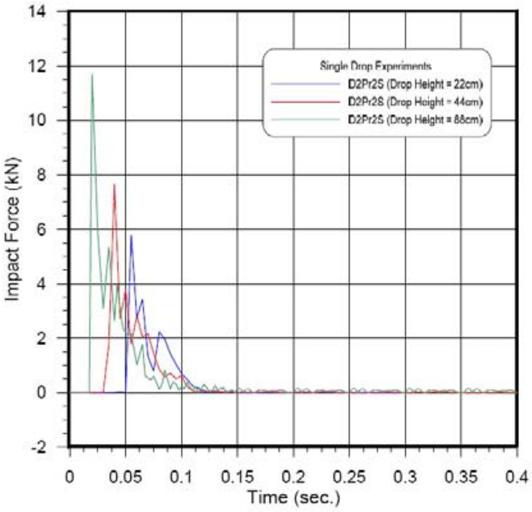

Figure 4 Impact Force Time History for Composite Beam (D2Pr2S)

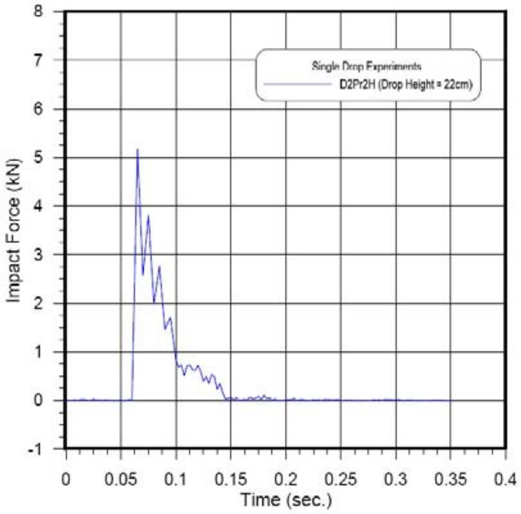

Figure 5 Impact Force Time History for Composite Beam (D2Pr2H)

Table (8) summarizes the results of the impact tests. It can be observed that the duration of impact forces, the time from the start of impact until the impact force starts to vanish, increases as the applied kinetic energy of the striker increases for the same tested beam. Also, the duration of impact gets longer as span length gets longer. This can be seen from the results recorded for the tested composite beams D1Pr1S and D2Pr1S, having the same cross sectional properties with 1.1 m and 2.3 m effective span length, respectively. The recorded duration of impact for each drop height is longer in beam D2Pr1S than in beam D1Pr1S. On the other hand, the tests results for the composite beams D2Pr1S and D2Pr2S, having same effective span length but with 18 mm and 37 mm plywood slab thickness, respectively, show that for each drop height, the duration of impact is shorter in beam D2Pr2S than in beam D2Pr1S. These results confirm the known fact that the duration of impact reduces with the increase of the stiffness of the tested beams. Also, it can be clearly seen from the results in Table (8) that the maximum developed impact forces for composite beam (D2Pr2S) are lager than those developed for composite beam (D2Pr1S) for the same drop heights and the maximum developed impact forces for composite beam (D1Pr1S) are also larger than those developed for composite beam (D1Pn1S) for the same drop heights. On the other hand, the developed maximum impact force from a drop height of 88cm, for example, on the composite beam (D1Pr1S) having 1.1m span length is (22.323 kN), While, the impact force is (8.726 kN) for the composite beam (D2Pr1S), which have the same cross section of specimen (D1Pr1S) but with 2.3m span length. This reveals that the maximum impact force produced from a drop weight increases with the increase of the stiffness of the tested beams. For any tested beam, it can be noted that when the height of the dropped weight is increased four times from 22cm to 88cm, the maximum impact force only increases by a ratio ranged between (1.78) for aluminum beam (DA1) to (2.02) for composite beam (D2Pr2S).

TABLE 8

CHARACTERISTICS OF IMPACT FORCES OF IMPACT TESTS

Group No.	Designation	Specimen No.	Drop Height (cm)	Applied Kinetic Energy (J)	Max. Impact Force (kN)	Duration of Impact (msec)
1	DA1	1	22	66.54	9.880	75
		2	88	266.15	17.599	100
2	D1Pr1S	1	22	66.54	11.675	53
		2	44	133.07	18.945	68
		3	88	266.15	22.323	81
3	D1Pn1S	1	22	66.54	10.445	58
		2	44	133.07	15.842	73
		3	88	266.15	20.224	85
4	DA2	1	22	66.54	3.541	88
		2	88	266.15	6.364	123
5	D2Pr1S	1	22	66.54	4.701	80
		2	44	133.07	6.340	95
		3	88	266.15	8.726	115
6	D2Pr2S	1	22	66.54	5.797	70
		2	44	133.07	7.653	82
		3	88	266.15	11.702	98
7	D2Pr1H	1	22	66.54	4.128	90
8	D2Pr2H	1	22	66.54	5.174	85

4.1.2 Midspan Deflection

Figures (6) to (9) show the time history response of midspan deflection of selected tested aluminum beam and composite beams.

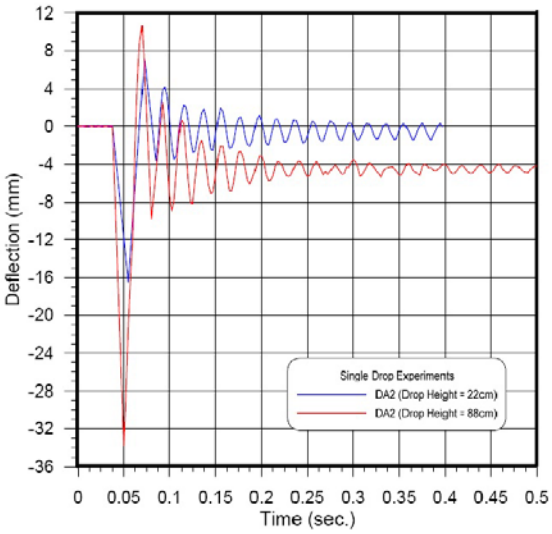

Figure 6 Midspan Deflection Time History for Aluminum Beam (DA2)

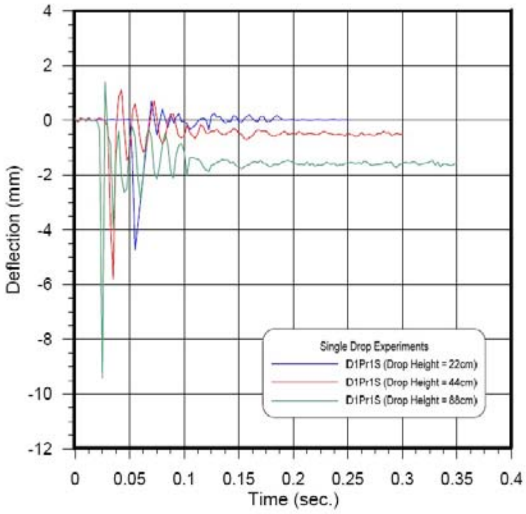

Figure 7 Midspan Deflection Time History for Composite Beam (D1Pr1S)

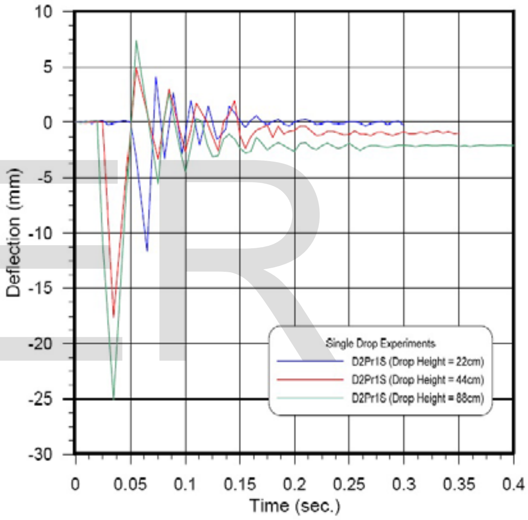

Figure 8 Midspan Deflection Time History for Composite Beam (D2Pr1S)

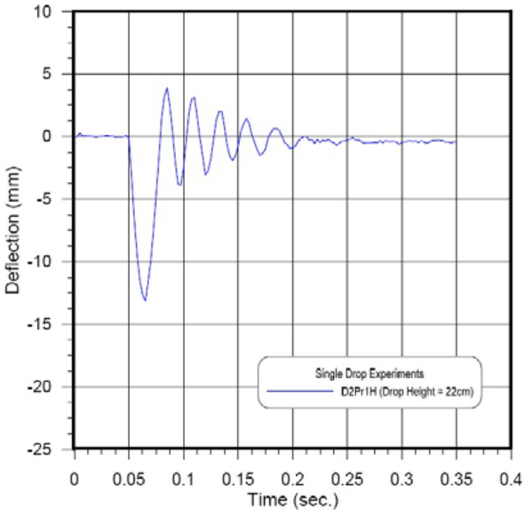

Figure 9 Midspan Deflection Time History for Composite Beam (D2Pr1H)

The time varying midspan deflection for all tested beams starts with a rapid increase to produce the maximum value and then decreasing, with an approximate harmonic response, to reach after several successive cycles a steady state.

It was observed that the variation of midspan deflection with time for all tested beams oscillates, after reaching their peak value, around values other than the zero deflection value (the original location of the tested beams). This may be due to that these tested beams may be permanent deflections, which increase with the increase of the height of the dropped weight and the oscillation occur around this value of deflection.

Table (9) summarized the results of the impact tests for all tested aluminum and composite beams.

TABLE 9

VALUES OF MIDSPAN DEFLECTION FOR IMPACT TESTS

Group No.	Designation	Specimen No.	Drop Height (cm)	Impact Velocity (m / sec)	Max. Midspan Deflection (mm)
1	DA1	1	22	2.078	5.529
		2	88	4.155	12.083
2	D1Pr1S	1	22	2.078	4.736
		2	44	2.938	5.795
		3	88	4.155	9.407
3	D1Pn1S	1	22	2.078	4.937
		2	44	2.938	7.031
		3	88	4.155	11.107
4	DA2	1	22	2.078	16.479
		2	88	4.155	33.835
5	D2Pr1S	1	22	2.078	11.634
		2	44	2.938	17.589
		3	88	4.155	25.070
6	D2Pr2S	1	22	2.078	9.492
		2	44	2.938	14.103
		3	88	4.155	18.945
7	D2Pr1H	1	22	2.078	13.153
8	D2Pr2H	1	22	2.078	10.713

As noted in the variation of maximum impact force with dropping height, it can be seen from the table above that the increase of the dropping height of the impact weight will not result in the same increasing rate in the developed maximum midspan deflection. When the height of the dropped weight is increased four times from 22cm to 88cm, the increase in the maximum mdispan deflection developed by the impact weight from dropping height of 88 cm is 2.25 times the maximum midspan deflection developed from dropping height 22 cm for the composite beam (D1Pn1S).

4.2 Numerical Results

4.2.1 Impact Force

In order for the finite element analysis results of the tested beams to be compatible with the experimental results, the method of calculation for the time history of the impact force for each tested beam must represent the experimental results, where the time history of the impact force is derived from the time history of the acceleration of the dropping weight. The maximum impact forces for each beam as calculated by using the finite element method for different drop heights are shown in Table (10).

The ratios of experimental to predicted values of maximum impact forces are (0.738) to (0.755) with an average value of (0.747) for the aluminum beams and (0.640) to (0.831) with average value of (0.719) for the composite beams. This deviation between the experimental and finite element analysis results may be attributed to that the finite element analysis gives larger impact forces because of the increase of the stiffness of the composite beams, resulting from the approximation adopted in the modeling of the displacement of these beams.

Figures (10) and (11) show a comparison of the experimental time histories and finite element analysis time histories of the impact force for selected tested beams. The finite element modeling is found to give time histories of the impact force closer to the experimental results.

4.2.2 Midspan Deflection

The finite element analysis is found to give close relationships to experimental results. Table (11) illustrates the comparison of the experimental results with the theoretical ones for maximum midspan deflection for each tested beam under impact force. The ratios of experimental to predicted values of deflection are (1.242) to (1.303) with an average value of (1.271) for the aluminum beams and (1.194) to (1.526) with average value of (1.367) for the composite beams. This may be due to the approximation adopted for the behavior modeling of the tested beams materials and the constraints theoretically stipulated on the deformation of beams.

Figures (12) and (13) illustrate the time varying of the midsapn deflection due to impact force for selected tested beams. The experimental relationships alongside the theoretical ones are collected for each beam with a selected drop height of the impact weight. Good agreement is obtained.

TABLE 10
COMPARISON BETWEEN EXPERIMENTAL AND FEA RESULTS OF MAXIMUM IMPACT FORCE FOR THE TESTED BEAMS

Group No.	Designation	Specimen No.	Drop Height (cm)	Max. Impact Force (kN)		F_{exp}/F_{FEA}
				Experimental (F_{exp})	FEA (F_{FEA})	
1	DA1	1	22	9.880	13.158	0.751
		2	88	17.599	23.659	0.744
2	D1Pr1S	1	22	11.675	16.457	0.709
		2	44	18.945	24.327	0.779
		3	88	22.323	30.003	0.744
3	D1Pn1S	1	22	10.445	14.871	0.702
		2	44	15.842	23.184	0.683
		3	88	20.224	29.728	0.680
4	DA2	1	22	3.541	4.795	0.738
		2	88	6.364	8.426	0.755
5	D2Pr1S	1	22	4.701	6.017	0.781
		2	44	6.340	8.813	0.719
		3	88	8.726	12.712	0.686
6	D2Pr2S	1	22	5.797	8.812	0.658
		2	44	7.653	11.952	0.640
		3	88	11.702	17.121	0.683
7	D2Pr1H	1	22	4.128	4.970	0.831
8	D2Pr2H	1	22	5.174	6.774	0.764

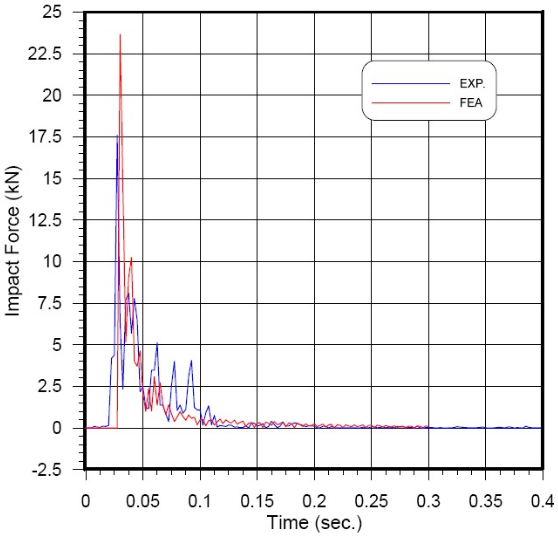

Figure 10 Impact Force Time History for Aluminum Beam (DA1) for Dropping Height of (88 cm)

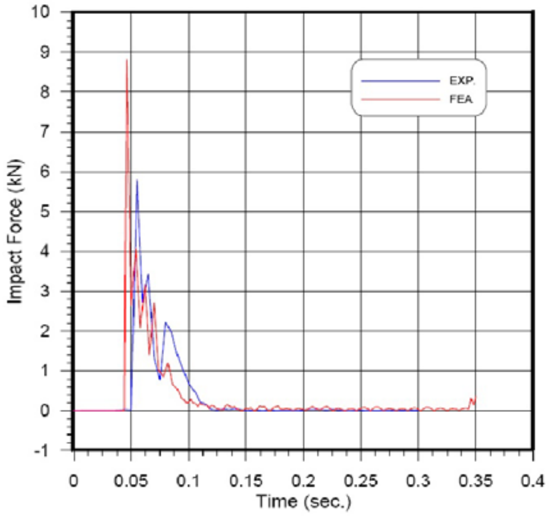

Figure 11 Impact Force Time History for Composite Beam (D2Pr2S) for Dropping Height of (22 cm)

TABLE 11
COMPARISON OF EXPERIMENTAL AND FEA RESULTS OF MAXIMUM MIDSPAN DEFLECTION FOR THE TESTED BEAMS

Group No.	Designation	Specimen No.	Drop Height (cm)	Max. Midspan Deflection (mm)		d_{exp}/d_{FEA}
				Experimental (d_{exp})	FEA (d_{FEA})	
1	DA1	1	22	5.529	4.402	1.256
		2	88	12.083	9.273	1.303
2	D1Pr1S	1	22	4.736	3.352	1.413
		2	44	5.795	4.434	1.307
		3	88	9.407	7.031	1.338
3	D1Pn1S	1	22	4.937	3.496	1.412
		2	44	7.031	4.649	1.512
		3	88	11.107	7.279	1.526
4	DA2	1	22	16.479	12.834	1.284
		2	88	33.835	27.235	1.242
5	D2Pr1S	1	22	11.634	9.102	1.278
		2	44	17.589	12.946	1.359
		3	88	25.070	19.108	1.312
6	D2Pr2S	1	22	9.492	6.737	1.409
		2	44	14.103	9.630	1.464
		3	88	18.945	13.659	1.387
7	D2Pr1H	1	22	13.153	11.018	1.194
8	D2Pr2H	1	22	10.713	8.762	1.223

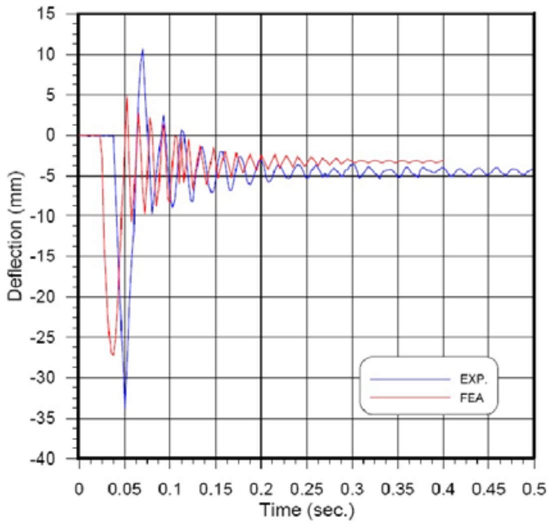

Figure 12 Midspan Deflection Time History for Aluminum Beam (DA2) for Dropping Height of (88 cm)

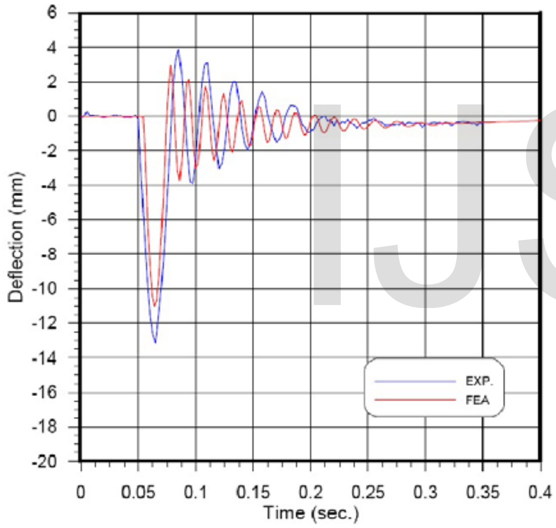

Figure 13 Midspan Deflection Time History for Composite Beam (D2Pr1H) for for Dropping Height of (22 cm)

5 CONCLUSIONS

An experimental study of the proposed timber aluminum composite beams has been achieved in this work program.

One of the main drawn conclusions from this study is that the maximum impact force developed by the dropped weight on such composite beams increases with the increase of the stiffness of these beams.

The duration of impact increases with the increase of the applied impact velocity (drop height of the impact weight), and it reduces with the increase of the beam stiffness.

The nonlinear finite element analysis by (ANSYS LS DYNA version 13.0) package program using three dimensional elements for modeling the timber aluminum composite beams gives acceptable agreement with the test results for overall response of the tested beams.

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