The Low-Velocity Impact Response of Laminated Composite Plates with Holes

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***Abstract*—Composite materials have been increasingly used because of their high specific strength and stiffness, good fatigue performance and corrosion resistance. This study investigated numerically and experimentally the low velocity impact on composite plate with and without holes. The numerical part was achieved by using ABAQUS 6.12 Finite Element analyzer while experimental work included the manufacturing of E-Glass/Polyester composite plate and calculated their mechanical properties. The determination of first five modes of composite plate under two boundary conditions (CCCC, SSSS) was done and the low velocity impact test was carried out to evaluate the displacement and contact force for composite plate under different velocities of the impactor without and with one and two holes of diameters (10)mm. Ultrasonic test was done to detect the damage that may be occurred because of the impact on composite plate. It was concluded that the presence of holes decreases the natural frequencies of the composite plate and absorbed energies by the plate and impact force, while the displacement of composite plate increase by increasing the numbers and diameters of the holes**.

Keywords—Low velocity impact, E-glass / polyester, Laminated composite plate, ABAQUS, Ultrasonic test.

1. Introduction

Composite materials are those constructed by combining two or more materials on a macroscopic level such that they have better engineering properties than the conventional materials, for example, metals. Some of the properties that can be improved by constructing composite materials are stiffness, strength, weight reduction, corrosion resistance, fatigue life and wear resistance**.** The majority of composite materials are created from two materials: a reinforcement material called fiber and base material called matrix material [1].The composite materials have many applications in the engineering field such as aircraft industries. In spite of many attractive qualities, composite materials do however suffer from poor resistance to impact loading .This results in damage that can cause severe structural degradation such as reduction in compressive strength. Impact test are used to study the dynamic deformation and failure modes of materials. The impact on composite plate can be divided according the velocity of the impactor to [2] 1- Low velocity impact (LVI):It results from tool drops, which occur at velocities less than 10m/s. (LVI) can be treated as quasi-static event the upper limit can vary from one to ten per second depending on target stiffness, material properties and the impactor mass and stiffness.2- Intermediate impact: it occurs in velocity from 10m/s to 50 m/s. It results from tornado and hurricane debris.3- High velocity (Ballistic) impact:Results from small arms fire or explosives warhead fragments at velocity range from 50m/s to 1000m/s. is dominated by stress wave propagation through the material, in which the structure does not have time to respond, leading to localized damage. 4- Hyper velocity impact:It usually occurs at velocity 2 km/s to 5 km/s. it results from the impact between meteors in the galaxies. Numerous papers and researches are studied the experimental and numerical simulation of low-velocity impact on composite structures. A.M.Amaro, P.N.B Reis, M.F.S.F de Moura, M.A Neto**[**3].The objective of this work is to evaluate effect of holes on the delamination that occurred by low velocity impact on Glass/Epoxy laminated composite plates have one and two holes were tested and the resulting damage was contrast with one of plate without holes. It was verified that the presence of holes increased the energy absorbed by the damage as well as the delamination areas. It also verified that the presence of holes have no remarkable effect influence on load –displacement and load-time relations. A.R. Setoodeh, A.ZafarEmily[4].Studied numerically the dynamic response of laminated composite plate subjected to impact loading by using the developed FE code which is based on layerwise laminate theory. The problem modeled by employing ABAQUS software. The study considered different boundary conditions (CCCC, SSSS, SFSF) and different velocities(1.27, 2.54, 3.81)m/s on contact force history and plate response. The impactor mass was 0.1 kg with radius 6.35mm. The plate stacking sequences are [0/90^o/0], [45^o/0/45^o] and[45^o/0/-45^o] with a hole radius is 6.35mm. The research showed that the plate response is approximately proportional to impact velocity. N.RajeshMathivanan, J.Jerald [5].This work presented the results of an experimental investigation about low velocity impact response of the woven glass fiber epoxy matrix composite laminates plates. Experimental tests were done according to ASTM standards using aninstrument of drop weight impact testing machine. The range of velocities was 2m/s to 4.5m/s. The response of these laminates plates to drop weight low velocity at energies levels from 3J to 15J was investigated. It was found that thelaminates showed two kinds of failure mode; crack initiation and perforation of the laminates.

In this work the low velocity impact on composite plate was done under differentvelocities of the impactor (1.4, 2.42, 3.13, 3.96)m/s for two boundaryconditions (CCCC, SSSS)withoutholes and with hole of diameter (10)mm in the center of the plate and two holes of diameters (10)mm on the left and right the center of plate so the distance between two holes are (8)cm.

2. ABAQUS Finite Element Analyzer:

ABAQUS is finite element modeling program designed for modeling a variety of materials behavior in both static and dynamic situations. The program has an extensive materials behavior library that allows for using data obtained from equations or from the testing laboratory to be directly input to the model definition. The advantages of ABAQUS are in process optimization, materials comparison, and general forming analysis. This allows for reducing time, effort and materials costs involved with trial and error manufacturing techniques. Perhaps the biggest advantage of ABAQUS that allows modeling at high level of detail. The user is able to setup a very detailed model describing various types of materials behavior. Moreover the software is command-line accessible and supports scripting functionality. ABQUS is used for complex materials such as rubbers, thermo-plastic, soil and composite. It is so suitable for contact, fracture and failure problem like impact, crash event and crack. Therefore, ABAQUS is used in automotive, aerospace, industry and in academic researches. S4R (shell-4nodes-reduced integration) is element type for thick and thin composite plate with 4-nodes, hourglass control and finite membrane strain with 6 degree of freedom (Ux , Uy , UZ , θx , θy , θz) was used to simulate the composite plate. C3D10M (Continuum 3D element-10 nodes –modified formulation) and it is the best element type for contact simulation and it used to simulate the impactor made of steel.

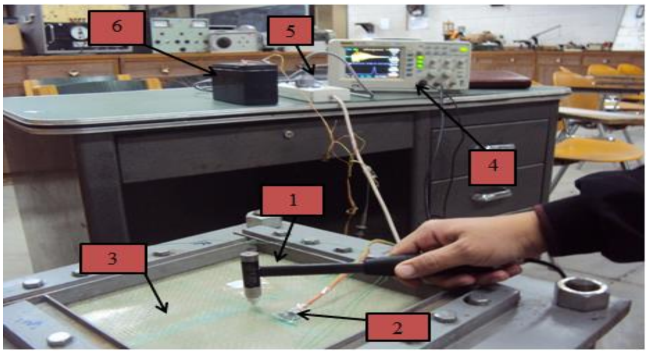
3. Material and experimental work procedure.

The composite material of E-Glass/Polyester was fabricated by using hand layup process with 4 layers and stacking sequence $[0/90^{o}]_{4s}$. The dimensions of the plate is (250 x 250 x 2.4)mm. The tensile test was done with specimen of dimension (250 x 25 x2.4)mm to determine the mechanical properties of woven composite plate such as Young modulus, shear modulus and Poisson ratio. The mechanical properties listed in table (I).

Table (I). The mechanical properties of woven composite plate.

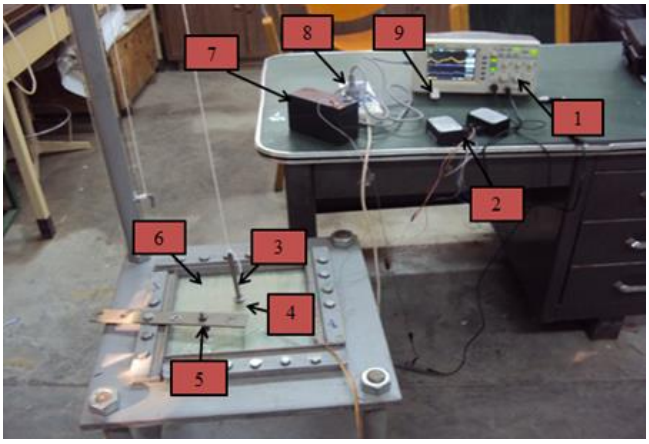
Properties	Value
Elastic modulus (E1w=E2w) (GPa)	17.153
Elastic modulus (E3w) (GPa)	9.523
Shear modulus in plane 1-2 (G12w) (GPa)	2.9
Shear modulus in plane 1-3 (G13w) (GPa)	2.773
Shear modulus in plane 2-3 (G23w) (GPa)	2.773
Poisson ratio in plane 1-2	0.1435
Poisson ratio in plane 1-3	0.4299
Poisson ratio in plane 2-3	0.4299

Vibration test was carry out on the woven composite plate with and without holes to find natural frequency. The plate is placed on the rig with different boundary conditions (CCCC, SSSS)as shown in figure (1) below. Impact hammer is used to excite the platewith impulse signal causing vibration of plate. ADXL 330 accelerometer fixed on the composite plate to transit the signal tooscilloscope (Rigol DS1102E). The oscilloscope is viewing the response of the specimen that is loaded by impact hammer which is connected to oscilloscope and generates the applied load to the plate. The oscilloscope presents the signal as wave with peaks that will give natural frequency.



Figure(1). Vibration test with (CCCC) boundary condition. 1- Impact hammer. 2- Accelerometer ADXL 330 .3-Composite plate.4-Oscillicsope 5- Power source. 6- battery.

The low velocity impact test was carried out with a rig which was designed and built for this purpose. The rig consist of lower and upper bases with square shape which connected to each other by four vertical rods with height (50)cm. the dimensions of square bases was (50 x 50)cm and the upper base has a place for composite plate with (25 x 25)cm. the rig also has vertical rod with length (100)cm and moving horizontal rod with length (50)cm. Two pulleys with diameter (60)cm were fixed in the horizontal rod so that the rope string which carry the impactor will pass over them. The masonry rope string and pulleys were lubricated so that to reduce the fraction between them. Eight pieces of metal with rectangular shape was manufactured to apply different boundary conditions. Every piece has a place for four bolts. The impactor was manufactured of steel with length of (13.5)cm and diameter (25)mm . The weight of impactor was (110)gm and the mass density was (7850)kg/m^3. The young modulus of the impactor was (200)Gpa and Poisson ratio (0.3). Composite plate was putin the rig with different boundary conditions (CCCC, SSSS) with strain gauge in the center of plate to measure the force and Hall Effect senor with magnetic to determine the displacement. The magnetic piece was fixed by a bolt and put exactly above the Hall Effect sensor so that the Hall Effect sensor can measure the displacement when the impactor hit the composite plate. Load cell amplifier was used to amplify the signal which was connected to oscilloscope (RIGO DS-1102E) as shown in figure (2). USB flash was used to get the results from oscilloscope and then the results was drawn by using excel software. The holes were done by using drill with different size of specially drill bits which was used for glass. The diameters of drill bits was (10)mm. Two cases of holes were study in this work. The first case was the hole at exactly at center of plate. The second case was two holes on theright and left of the center of the plate and the distance between each hole around the center was (4)cm so, the total distance between two holes was (8)cm.



Figure(2). The low velocity impact test.1-Oscilliscope.2-Load cell amplifier 3-Impactor.4-Strain gauge.5-Hall effect sensor.6-Composite plate 7-Battery.8-Power source.9-USB flash.

In order to investigate the location of damage such as delamination or matrix crack that may be happened during the low velocity impact test or drilling operation, the non-destructive method represented by the ultrasonic technique was used. The ultrasonic device (PROCEQ PANDIT LAB) was calibrated by using calibrated rod so that to ensure from the results. The regions in the composite plate that subjected to impact load and around the holes were tested. The ultrasonic device connected to the computer to show the results and two transducers put in front of and behind the composite plate to send and receive the wave as shown in figures (3).

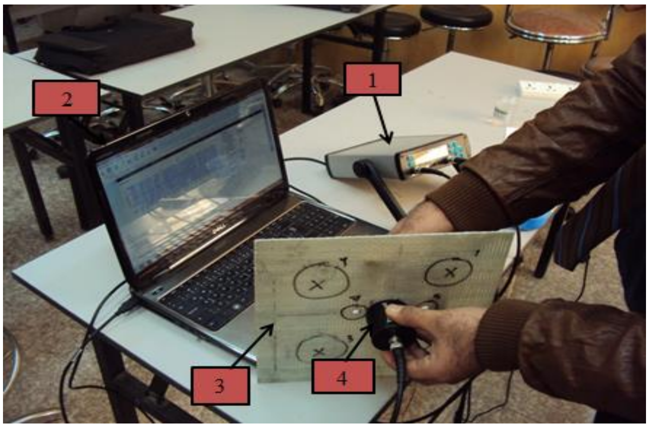


Figure (3). Ultrasonic test for composite plate with two holes . 1- PROCEQ PANDIT LAB. 2- Computer. 3- Composite Plate. 4- Transducers.

One of the transducer send the wave and the other one receive it. If the tested region had not damage the result in the computer will be showed as uniform wave response. If the tested region had the damage, the results will be showed in the computer as non-uniform wave response. The wave need to time about (0.9 microsecond) and velocity (3333.39 m/s) to transit from one transducer to another. This test showed that the composite plate did not have any damage caused by low velocity impact test, but the composite plate had damage around the holes caused by drilling operation.

4. The Results and Discussions.

The results of vibration test can be summarized as below:

For intact plate under (CCCC), the maximum error parentage was (2.83%), while the maximum error percentage for composite with one hole with diameter (10) mm was (3.3%) with maximum decreasing percentage (1.64%) and for composite plates with two holes of diameters (10)mm the maximum error percentage was (1.83%) with maximum decreasing parentage (1.85%). For the intact composite plate under (SSSS) boundary condition, the maximum error percentage was (0.42%), while the maximum error percentage for composite plate with one hole of diameter (10)mm was (1.68%) with maximum decreasing percentage (1.96%) and for composite plate with two holes of diameters (10)mm the maximum error percentage was (3.56%) with maximum decreasing percentage (2.24%).

Table (II). A comparison of natural frequency (Hz) of $(0/90^o)_4$cross-ply plates without holes between the ABAQUS program and experimental work

Case of Boundary Conditions	Results	Mode number (Hz)				
		1	2	3	4	5
CCCC	ABAQUS	219.06	452.83	634.10	838.07	981.51
	Experimental	216	440	637	840	991
	Error percentage (%)	1.4	2.83	0.46	0.23	0.96
SSSS	ABAQUS	108.79	291.70	436.15	615.85	732.74
	Experimental	109	292.2	438	618	733
	Error percentage (%)	0.2	0.17	0.42	0.35	0.035

Table(III) A comparison of natural frequency (Hz) of $(0/90^{o})_4$ cross-ply plates with one hole (D=10mm) between the ABAQUS program and experimental work.

Case of Boundary Conditions	Results	Mode number (Hz)				
		1	2	3	4	5
CCCC	ABAQUS	218.01	448.89	630.15	824.30	971.47
	Experimental	225.2	452.8	635	837	977
	Error percentage (%)	3.3	0.87	0.77	1.54	0.56
SSSS	ABAQUS	108.37	289.78	432.29	603.73	722.16
	Experimental	110.2	291	438	611	739.5
	Error percentage (%)	1.68	0.42	1.32	1.2	2.4

Table (IV) A comparison of natural frequency (Hz) of $(0/90^{o})_4$cross-ply plates with two holes (D=10mm) between the ABAQUS program and experimental work.

Case of Boundary Conditions	Results	Mode number (Hz)				
		1	2	3	4	5
CCCC	ABAQUS	217.91	447.02	628.90	822.54	968.05
	Experimental	221.9	450	634.7	827.8	975
	Error percentage (%)	1.83	0.66	0.92	0.64	0.71
SSSS	ABAQUS	108.14	289.2	430.07	602.02	721.32
	Experimental	112	288	438	610.8	729
	Error percentage (%)	3.56	0.41	1.84	1.45	1.06

The results of absorbed energies obtained numerically by using ABAQUS finite element analyzer. The results contained different cases to study the effect of boundary conditions, velocity of impactor , locations and number of holes. It was assumed that the impactor hit the center of the plate for the all cases It was also observed that the absorbed energies in all boundary conditions decrease by increasing the numbers and diameters of holes because of the stress contour in intact plate is more than the stress contour in the plate with one or two holes as shown in figure figure(4) ,figure (5) and figure (6). The absorbed energies decrease with increasing the velocity of the impactor.

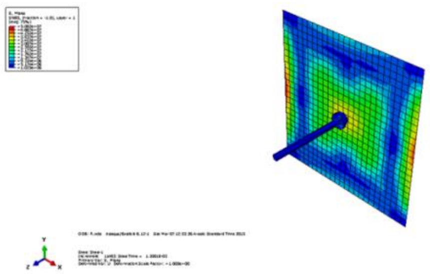


Figure (4) Stress contour for composite plate without hole at (CCCC) boundary condition.

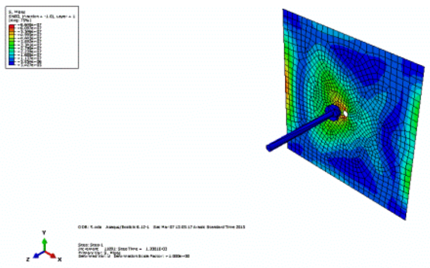


Figure (5) Stress contour for composite plate with one hole of diameter (10) mm at (CCCC) boundary condition.

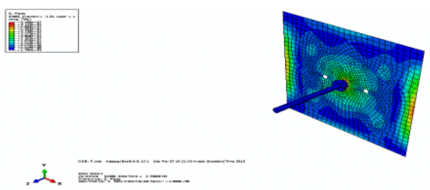


Figure (6) Stress contour for composite plate with two holes of diameter (10) mm at (CCCC) boundary condition

Table(V) Absorbed energies for composite plate without holes.

Case of boundary conditions	Impact Velocity(m/s)	Impact Energy (J)	Max. Absorbed Energy (J)	Percentage of Absorbed Energy (%)
CCCC	1.4	0.1078	0.098	90.90
	2.42	0.3221	0.2865	88.94
	3.13	0.538	0.474	88.10
	3.96	0.8624	0.743	86.15
SSSS	1.4	0.1078	0.090	83.48
	2.42	0.3221	0.267	82.89
	3.13	0.538	0.440	81.78
	3.96	0.8624	0.690	80.00

Table (VI) Absorbed energies for composite plate with one hole (D=10mm).

Case of boundary conditions	Impact Velocity (m/s)	Impact Energy (J)	Max. Absorbed Energy (J)	Percentage of Absorbed Energy (%)
CCCC	1.4	0.1078	0.0953	88.40
	2.42	0.3221	0.281	87.23
	3.13	0.538	0.460	85.50
	3.96	0.8624	0.730	84.64
SSSS	1.4	0.1078	0.085	78.84
	2.42	0.3221	0.252	78.23
	3.13	0.538	0.416	77.32
	3.96	0.8624	0.660	76.53

Table (VII) Absorbed energies for composite plate with two holes (D=10mm) .

Case of boundary conditions	Impact Velocity (m/s)	Impact Energy (J)	Max. Absorbed Energy (J)	Percentage of Absorbed Energy (%)
CCCC	1.4	0.1078	0.092	85.34
	2.42	0.3221	0.269	83.51
	3.13	0.538	0.445	82.71
	3.96	0.8624	0.695	80.58
SSSS	1.4	0.1078	0.084	77.92
	2.42	0.3221	0.243	75.44
	3.13	0.538	0.434	75.09
	3.96	0.8624	0.633	73.39

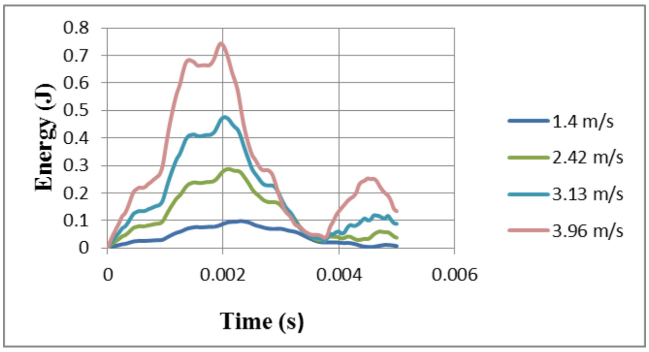


Figure (7) Absorbed energies for composite plate without holes at (CCCC) boundary condition.

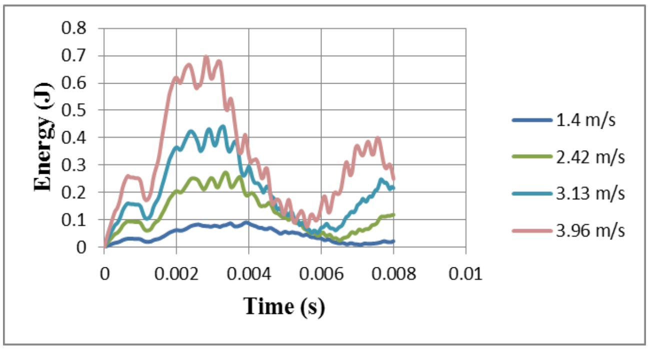


Figure (8) Absorbed energies for composite plate without holes at (SSSS) boundary condition.

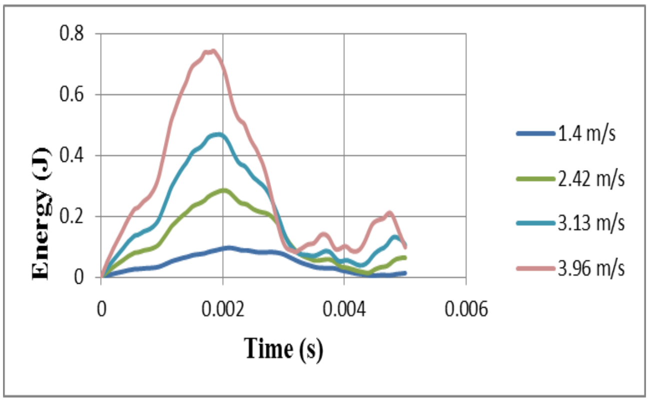


Figure (9) Absorbed energies for composite plate with one hole (D=10mm) at (CCCC) boundary condition.

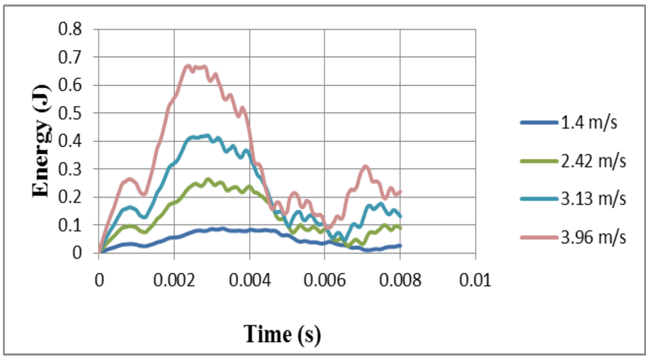
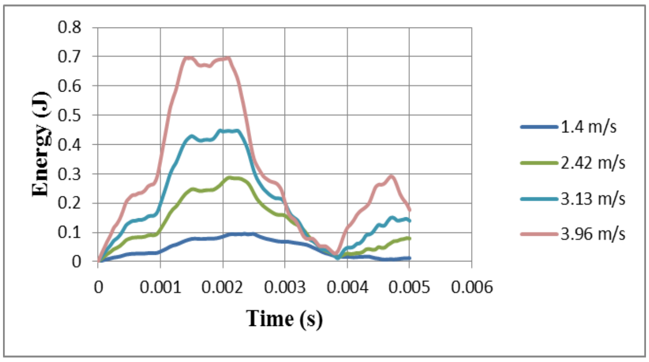


Figure (10) Absorbed energies for composite plate with one hole (D=10mm) at (SSSS) boundary condition.



Figure(11) Absorbed energies for composite plate with two holes (D=10mm) at (CCCC) boundary condition.

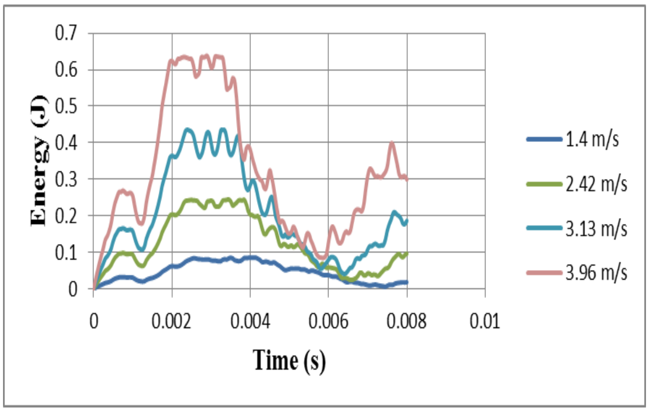


Figure (12) Absorbed energies for composite plate with two holes (D=10mm) at (SSSS) boundary condition.

The results of displacement for composite plate under low velocity impact were obtained numerically by using ABAQUS and experimentally by low velocity impact test to make comparison between them to calculate the error percentage.

Table (VIII) Comparison of Max.Displacement between ABAQUS and experimental work for composite plate without holes.

Case of boundary conditions	Impact Velocity (m/s)	Max. Displacement ABAQUS (mm)	Max. Displacement Exp. Work (mm)	Error percentage (%)
CCCC	1.4	0.443	0.437	1.35
	2.42	0.690	0.676	2.02
	3.13	0.910	0.917	0.77
	3.96	1.140	1.171	2.72
SSSS	1.4	0.980	0.989	0.92
	2.42	1.600	1.620	1.25
	3.13	2.000	2.01	0.50
	3.96	2.460	2.469	0.365

Table(IX) Comparison for Max. Displacement between ABAQUS and experimental work for composite plate with one hole (D= 10mm).

Case of boundary conditions	Impact Velocity (m/s)	Max. Displacement ABAQUS (mm)	Max. Displacement Exp. Work (mm)	Error percentage (%)
CCCC	1.4	0.518	0.527	1.74
	2.42	0.834	0.851	1.9
	3.13	1.091	1.11	1.75
	3.96	1.354	1.370	1.18
SSSS	1.4	1.267	1.289	1.74
	2.42	2.04	2.12	3.92
	3.13	2.530	2.547	0.67
	3.96	3.150	3.181	0.98

Table (X)Comparison of Max. Displacement between ABAQUS and experimental work for composite plate with two holes (D= 10mm) .

Case of boundary conditions	Impact Velocity (m/s)	Max. Displacement ABAQUS (mm)	Max. Displacement Exp. Work (mm)	Error percentage (%)
CCCC	1.4	0.534	0.540	1.12
	2.42	0.860	0.876	1.86
	3.13	1.110	1.115	0.45
	3.96	1.380	1.402	1.60
SSSS	1.4	1.320	1.351	2.3
	2.42	2.220	2.241	0.94
	3.13	2.640	2.661	0.79
	3.96	3.240	3.264	0.74

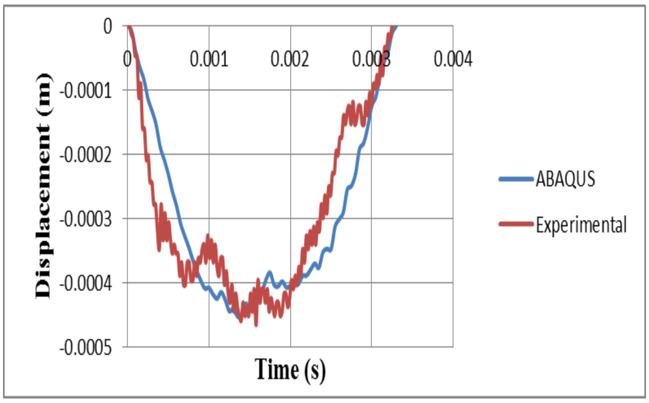


Figure (13) Comparison between ABAQUS and experimental work for composite plate without holes with (CCCC) boundary condition and velocity of impactor (1.4) m/s.

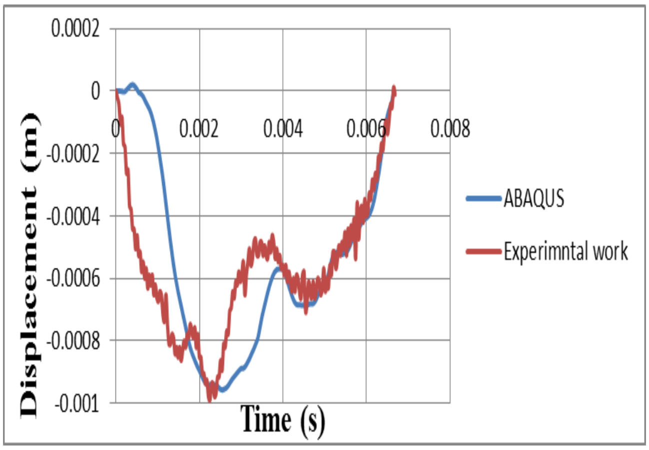


Figure (14) Comparison between ABAQUS and experimental work for composite plate without holes with (SSSS) boundary condition and velocity of impactor (1.4) m/s.

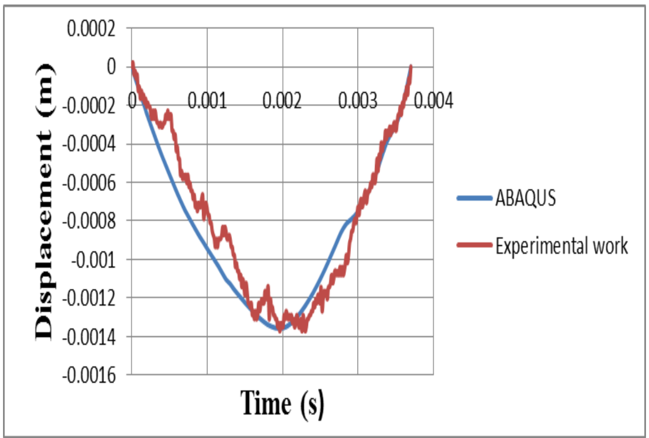


Figure (15) Comparison between ABAQUS and experimental work for composite plate with one hole (D= 10) mm at (CCCC) boundary condition and velocity of impactor (3.96) m/s.

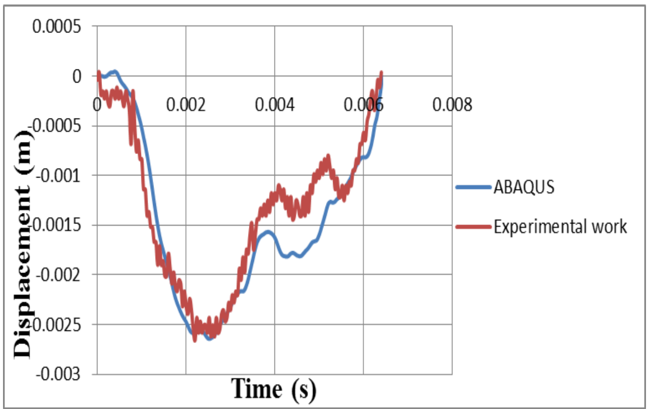


Figure (16) Comparison between ABAQUS and experimental work for composite plate with two holes (D= 10)mm at (SSSS) boundary condition and velocity of impactor (3.13) m/s.

The contcat force for composite plate was obtained numerically by using ABAQUS finite elemnet analyzer by taking an elemnt exactly at the point where the impactor hit the composite plate . The composite plate was taken under (CCCC) boundary condition with two velocities of impactor (1.4)m/s and (3.96)m/s without hole and with hole of diameter (10)mm in the center of the plate and another case was composite plate with two holes on the right and left the center of the plate with total distance between them (8)cm.

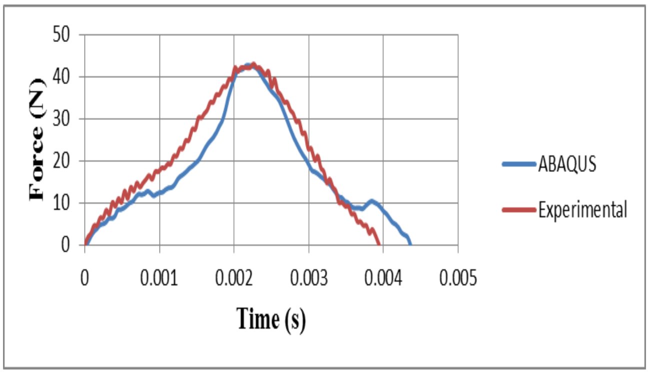


Figure (17) Comparison of contact force between ABAQUS and Experimental work for composite plate at (CCCC) boundary condition without holes and the velocity of the impactor (1.4)m/s.

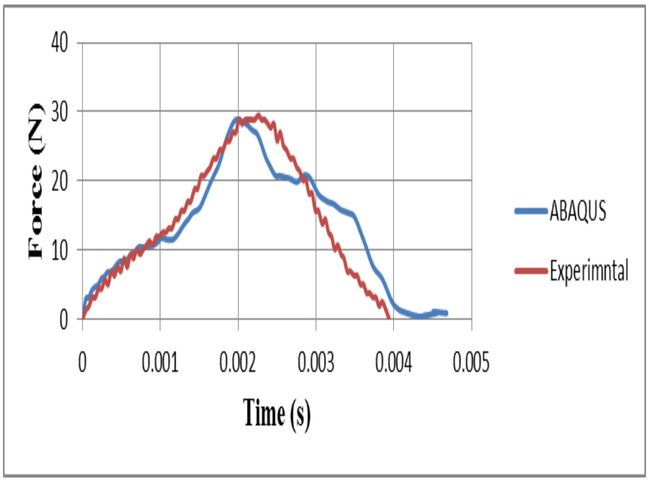


Figure (18) Comparison of contact force between ABAQUS and experimental work for composite plate with one hole (D= 10)mm at (CCCC) boundary condition and velocity of impactor (1.4)m/s.

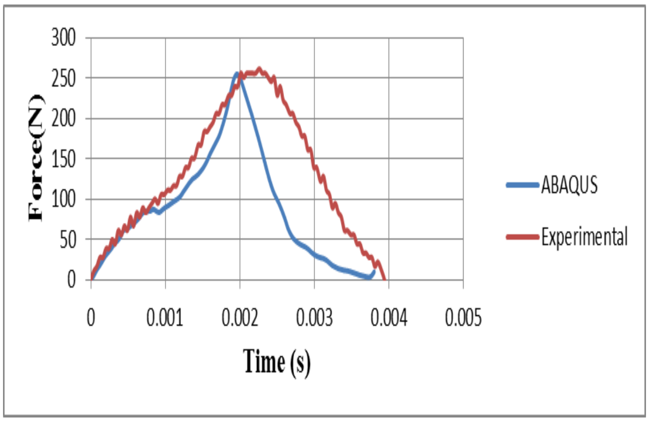


Figure (19) Comparison of contact force between ABAQUS and Experimental work for composite plate at (CCCC) boundary condition without holes and the velocity of the impactor (3.96)m/s.

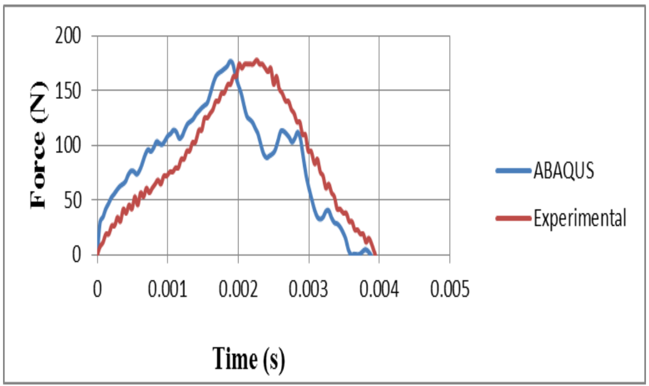


Figure (20) Comparison of contact force between ABAQUS and Experimental work for composite plate at (CCCC) boundary condition with one hole (D=10)mm and the velocity of the impactor (3.96)m/s.

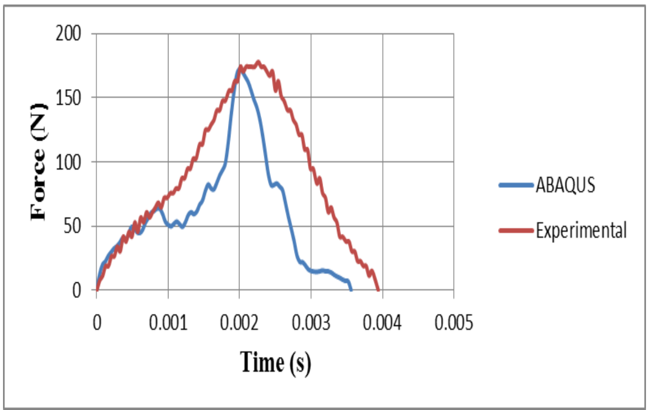


Figure (21) Comparison of contact force between ABAQUS and Experimental work for composite plate at (CCCC) boundary condition with two holes (D=10)mm and the velocity of the impactor (3.96)m/s.

5. Conclusions.

The low velocity impact on composite plate led to the following conclusions:

For the natural frequencies of composite plate, the maximum natural frequency occurred in composite plate without holes for (CCCC) boundary condition and decreased by increasing numbers and diameters of holes because of decrease the stiffness of the plate with presence of holes. For absorbed energy of the composite plate, the maximum absorbed energy occurred in (CCCC) boundary condition and then at (SSSS) boundary condition and it decrease by increasing the impact energy. It was also decreased by increasing numbers and diameter of holes. For the displacement of the composite plate, the maximum displacement occurred in (SSSS) boundary condition, then in (CCCC) boundary conditions was the minimum displacement. It was cleared that the displacement increased by increasing the numbers and diameters of holes. The displacement also increased by increasing the velocity of the impactor. For the contact force, it increased by increasing the velocity of the impactor. The contact force decreased with presence of holes and it also reduced by increasing numbers and diameter of holes. The composite plate in (CCCC) boundary condition need time less than the composite plate in (SSSS) boundary condition to reach the maximum displacement and maximum absorbed energy because of the stability of composite plate in (CCCC) boundary condition.

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