All Sciences Proceedings
http://as-proceeding.com/

5th International Conference on Applied Engineering and Natural Sciences

July 10-12, 2023 : Konya, Turkey

https://www.icaens.com/

Contact force of composite plate impacted at low energy alteration by hygrothermal conditions

Mustapha RABOUH*, Kamel ZOUGGAR[2,3] and Khelifa GUERRAİCHE [4]

[1]Development in mechanics and materials (LDMM), university of Ziane Achour, Djelfa, Algeria
[2]School of Engineering Sciences, Djillali Liabès University of Sidi Bel-Abbès, Algeria
[3]2Structures and Solids Mechanical Laboratory, Djillali Liabès University of Sidi Bel-Abbès, Algeria, BP 89, Cité Ben M'hidi, Sidi Bel-Abbès, 22000, Algeria
[4]Mechanical Engineering department, university of Batna 2, Batna, Algeria

*(1700ham@gmail.com) Email of the corresponding author

Abstract – Quite recently, considerable attention has been paid to the phenomena of impact. To enrich and give more light on the phenomena, this work is presented to give a comprehensive account of the effect of contact force due to an impact on composite plate subjected to an hygrothermal conditions specially those made of Glass/Polyester.

A comparative study between an experimental data obtained by [1] from impact tests to those obtained by simulations was firstly conducted. Based on the obtained results, it can be concluded that model reproduce very successfully the experimental studies.

The obtained numerical forces will be then used in Modde V 5.0 software to establish an DOE plan 'design of experiments'. Two factors are taken into consideration: the absorbed mass of water by the material and the drop height of the projectile and their effects on the numerical contact force.

From the results it has been carried out that the numerical contact force is reduced for aged plates. The most influencing parameter is the drop height of the projectile. An important implication of these findings is that a mathematical model is established which governs the contact force in the domain studied.

Keywords – Aged Composite; Impact; Design Of Experiment (DOE).

I. Introduction

In the last few years there has been a growing interest in using bonded fibre reinforced polymer composites (CFRP) for different fields of constructions such as in mechanical and civil engineering [1]. Composite materials bring much solution to designers and manufacturers but also cause many problems. For sustainable and light constructions, CFRP are used as beams and columns in structures. However, because they are surrounded by environment composites are also affected by climate variations resulting in moisture and temperature gradients [2].

Some research has been conducted to investigate the long-term performance of the FRP experimentally under environmental conditions [3, 4]. Until now, however, the effects of the harsh environments on the bond is not yet completely understood, e.g., water immersion, high humidity exposure or freeze-thaw cycles [5].

The durability of CFRP under moisture exposure is largely controlled by the rate at which water and deleterious ions that use water as a carrier over through the system [6]. The interface at bonded interfaces and constitute materials are susceptible to water uptake. It is necessary to understand the effect of the moisture diffusion in the CFRP. Absorbed moisture in a substance may bring in hygrothermal stress. Therefore, the moisture diffusion on the hygrothermal stress was analysed subsequently. Many researchers have modelled the moisture diffusion in a CFRP sheet/plate or in the bond area between CFRP layers, and it was found that results are difficult to translate into the subsequent analysis in simulations [7].

Quite recently, considerable attention has been paid to the study of the effect of this environmental parameters on choc absorption to perform a structural health monitoring and safety conditions [8]. The literature review suggest that research on the low velocity impact response of composite under a controlled hygrothermal environment is very limited. Impact modelling results in contact stresses (impact force) that may result in matrix cracking or induce delamination inside the composite material [4]. The longevity of such structures may be further aggravated due to the presence of thermal and moisture strains inside the laminates when operating in hygrothermal environments.

In this regards, the present study focused on modelling and analysing the effect of hygrothermal environment on the recorded contact force of composite plate made of polyester matrix reinforced with S-glass fibres subjected to low impact using finite elements code ABAQUS/Explicit. The investigation is conducted on two phases. For the first phase, a numerical modelling of low velocity impact is performed, then a comparison of the contact force results obtained numerically and those found experimentally by [8] on aged and non-aged plates under environmental effects are exposed. In a second phase, the results of the numerical contact force are injected in MODDE 5 software [9] to establish a DOE to reveal the most influencing parameters and setting a mathematical model which governs the contact force in the domain studied.

II. NUMERICAL MODELLING PROCEDURES

II.1. MATERIAL

In order to verify the validity of the numerical modelling with the experimental findings available in the work of [8], a composite plate with C3D8R elements is impacted by low velocity projectile with hemispherical ending.

To establish that a numerical simulation model using F.E code ABAQUS/Explicit is used to envelope all problem variables with association of an implemented subroutine VUMAT (Fig. 1). The S-Glass/Polyester plates are modelled with the following stacking sequence $(0_3/90)_S$ with the following dimensions: $150 \times 100 \times 4.5\,mm^3$.

The material proprieties and diffusivity constants in the three primary axes vbf are shown in Table 1. Diffusivities for unidirectional composites are defined as:

$D_x = D_{11}$ *is diffusivity parallel to the direction of the fibre in a lamina;*

$D_y = D_{22}$ *in the direction perpendicular to the fibre orientation in the lamina;*

$D_z = D_{33}$ *is diffusivity through the thickness of the stacked laminate.*

Table 1: Mechanical and hygrothermal properties of S-Glass/Epoxy Plate.

Fibre V_f	3.40000E-01
Thickness (mm)	0.00000E+00
E_{11} (MPa)	3.19141E+04
E_{22} (MPa)	6.64106E+03
E_{33} (MPa)	6.64106E+03
G_{12} (MPa)	2.27120E+03
G_{13} (MPa)	2.27120E+03
G_{23} (MPa)	2.17689E+03
NU_{12}	3.10628E-01
NU_{13}	3.10628E-01
NU_{23}	5.21721E-01
CTE_1 (mm/mm/C)	2.48764E-05
CTE_2 (mm/mm/C)	2.23585E-04
CTE_3 (mm/mm/C)	2.23585E-04
$D_{11}=D_{22}=D_{33}$ mm^2/s,	3.06000 E-12
$^{+}S_1$ (MPa)	1.56060E+03
$^{+}S_2$ (MPa)	5.49168E+01
$^{-}S_1$ (MPa)	-8.32999E+02
$^{-}S_2$ (MPa)	-2.69726E+02
S_{12} (MPa)	1.12859E+02
$^{-}e_1$ (mm/mm)	-2.61013E-02
$^{-}e_2$ (mm/mm)	-4.06149E-02
e_{12} (mm/mm)	4.96914E-02
K_1 (W/mm/K)	5.57763E-04
K_2 (W/mm/K)	1.66348E-04
K_3 (W/mm/K)	1.66348E-04
Density (g/mm3)	1.60488E-03

Note. 1

Three energy levels impact corresponding to three drop heights respectively: $E_1 = 9J \rightarrow H = 0.5m$ $E_2 = 13J \rightarrow H = 0.75m$ and $E_3 = 18J \rightarrow H = 1m$ were simulated. In this papers, just the first level was presented to show the agrees between experiments and the numerical model.

II.2. SIMULATION CONDITIONS ARE [10]:

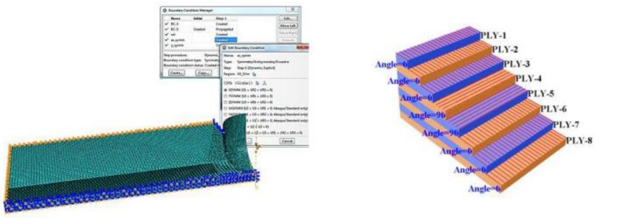
Boundaries conditions (BCs): To assure the same BCs of [8], the plate supports are fixed to bloc translation in z plane and lets the other freedom degrees free. In the impactor we just released the z translation.

Loading: Two methods can be used to load impactor. The first is varying the drop high and introduce gravity as load for the striker. The second is introducing a predefined field expressed by the impact velocity for each drop high value. In this case, the contact is assured between the plate and impactor. The two methods lead to the same results.

Time of simulation: The time of simulation is the contact time duration token from the experimental data, divided by the number of increments to finish the step.

The hygrothermal condition is expressed in term of moisture which is applied to the simulated samples on the top surface and on the four sides while the bottom is insulated. Since moisture equilibrium content is not dependent upon the direction of the fibres, the equilibrium value was the same in different directions.

Note. 2 All BCs and loadings are represented in respectively in Fig.1 and Fig. 2



(a) Assembly of the two part with BCs show (b) Plate staking configuration $(0_3/90)_S$

Figure.1. Modelling of the impact test

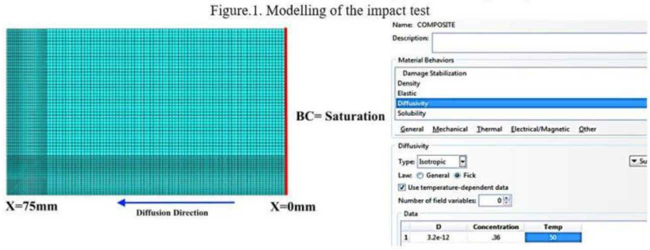


Figure. 2. Quarter Model in ABAQUS for Diffusion convergence Analysis

The ABAQUS model needs to produce accurate results for both relatively short periods of time (120 days) and for much longer periods so another analysis was run to simulate 5000^2 seconds using the same model. The 289 days simulated analysis is performed using the real conditions of 50°C with 95% RH and the boundary conditions were applied in the same manner as experiments drived by [8].

II.3. COMPARISON OF THE CONTACT FORCE COMPUTED VERSUS EXPERIMENTED

Values of the contact force at node through the centre of the plates were graphed in Figure. 3(a), (b) and (c) for the first energy level of 9J (Drop high H=0.5m) in the two cases of aged and non-aged specimens.

Numerical and experimental results of the contact force were compared to determine the efficiency of the numerical model. It is observed that the contact forces show the same mathematical curves for both plates under hygrothermal conditions and those non-aged seen Figure.3 (b). A delay is registered on the contact force in the aged plates; This can be explained by the spongious effects due to the moisture adsorption in the plate.

The overall measurement results summarized in Table 2, it is noted that the F_{IMP}^{MAX} value matches with a light difference to those obtained experimentally.

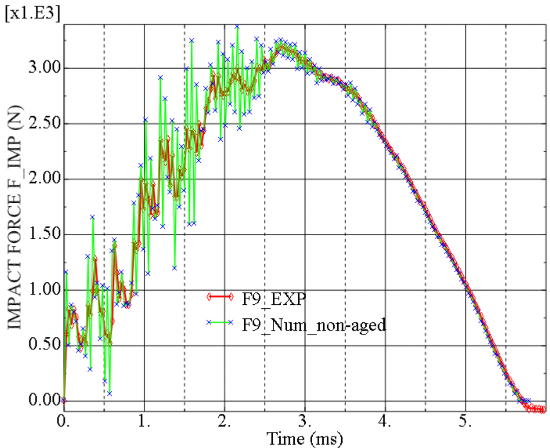
The experiments and the simulation indicate that the maximal contact forces F_{IMP}^{MAX} decreases with increases of the moisture concentration.

After analysis of impact phenomena under hygrothermal conditions it can be said that the adsorption can have a benefit effect in decreasing impact forces see Figure.4. In the other hand, after a threshold of concentration, this will be a disadvantage because it will create damages in the composite structure.

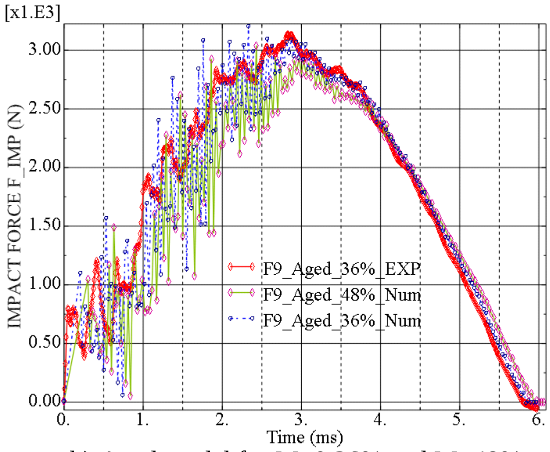
It is found that modelling approach represents a big advantage on the reproducibility of the experimental tests numerically without having time restraint for example the numerical values of F_{IMP}^{MAX} in the table case of the drop high of.

Table. 2. Records of the Maximum value of the contact forces.

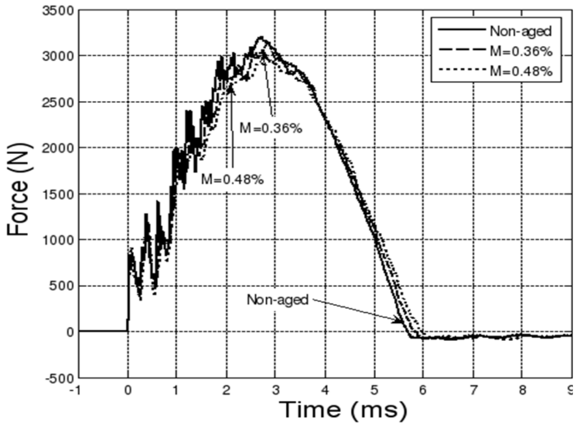
H (m)	***M (%)***	***F_{Exp} (N)***	***F_{Num} (N)***	***Error (%)***
0.5	0	3217	3257	1.24
2	0	3730	3772.56	1.14
3	0	4171	4201	0.7
4	0.36	3140	3181.12	1.31
5	0.36	3702	3748.43	1.2
6	0.36	//	4146.25	//
7	0.48	3002	3039.27	1.2
8	0.48	3500	3543.46	1.29
9	0.48	//	3997.67	//



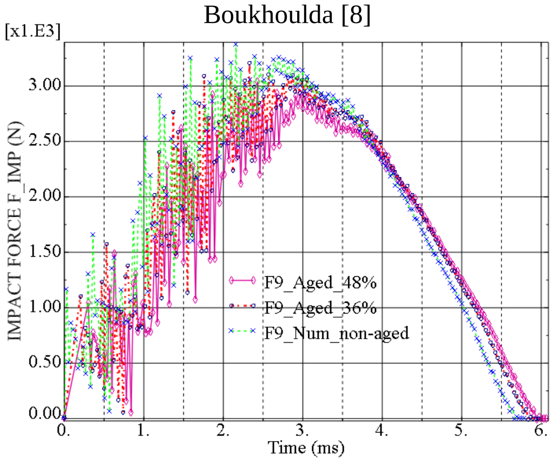
a) Non-aged numerical model in comparison with Boukhoulda experimental data[8]



b) Aged model for M=0.36% and M=48%; Numerical versus experimental records of Boukhoulda [8]



c) Experimental records of aged specimen [8]



d) Numerical records of contact force in aged specimen

Fig 3. Average Impact Force for 9J energy

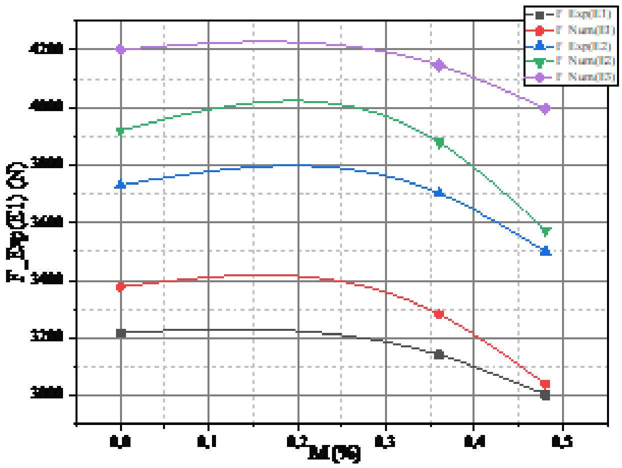


Figure.4. Maximum values of the contact forces as function as the moisture and the energy level.

III. DESIGN OF EXPERIMENTS (DOE)I MPLEMENTATION

Experimental design is how to conduct and plan experiments in order to extract the maximum amount of information from the collected data (. The basic idea is to vary all relevant factors simultaneously x_i as drop high 'H' and moisture values 'M' in this case of study, over a set of planned experiments, and then connect the results expressed in terms of the quantity of interest y (numerical contact force) by means of a mathematical model. This model is then used for interpretation, predictions and optimization.

Both factors 'H' and 'M' are represented by a graduated and oriented axis as shown in Figure. 5. The Design Space is established to estimate the area of operability or robustness. The range of variation of each factor is defined by a low level noted -1 and a high level noted +1. This arrangement permits the elaboration of the design matrix, see Table. 3.

Such a designed plan in which each of the two factors has only two levels is referred to as Factorial plan of 2^2.

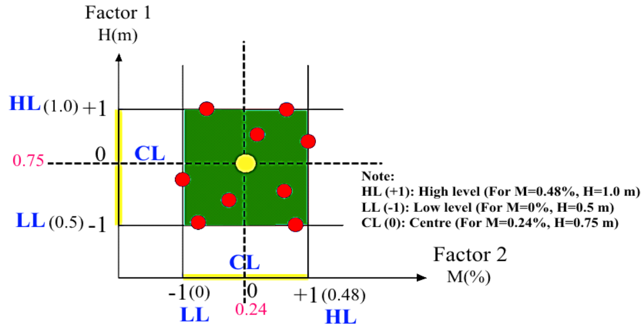


Fig. 5. Design space of experiments

Table.3. Design matrix

Experience N°	Factor 1 : High(m)	Factor 2 : Moisture(%)
1	-1	-1
2	1	-1
3	-1	1
4	1	1
5	-1	0
6	1	0
7	0	-1
8	0	1
9	0	0

III.1 MATHEMATICAL MODEL

To highlight how vary the response, according to each factor and improve their interaction a DOE plan is established using the Modde V5 software [9]. A Central Composite Designs Face Centred (CCF) plan is chosen [9, 11]. A system of 9 equations with 6 unknowns is resolved. Thus, the following equation is obtained

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_{12} x_1 x_2 + a_{11} x_1^2 + a_{22} x_2^2 + e \qquad (1.1)$$

The determination of the coefficients and a_{22} of the model is obtained using Multiple Linear Regression (MLR) in order to minimize the sum of squares of the residuals.

III.1.1 QUALITY OF PREDICTIVE MODEL

The efficiency of the predictive model fit by examining the following plots and lists:

The Summary of the fit, R^2, Q^2 represented on Figure.6 describe the quality and validity of the model; According to the obtained results were R^2, Q^2 tend to 1(see the Analysis of Variance Table. 4), it is concluded that quality of the model predicting contact force is highly successful. All this parameters effect plots for screening designs

Table. 4 The Analysis of Variance (ANOVA) summary

Numerical Contact Force	DF	SS	MS (variance)	F	p	SD
Total	9	1,21625e+08	1,35139e+07			
Constant	1	1,20171e+08	1,20171e+08			
Total corrected	8	1,45394e+06	181742			426,312
Regression	5	1,45266e+06	290532	681,008	**0,000**	539,01
Residual	3	1279,86	426,62			20,6548
	N = 9	Q2 =	0,994	Cond. no. =	5,759	
	DF = 3	R2 =	0,999	RSD =	20,65	
		R2 adj. =	0,998			

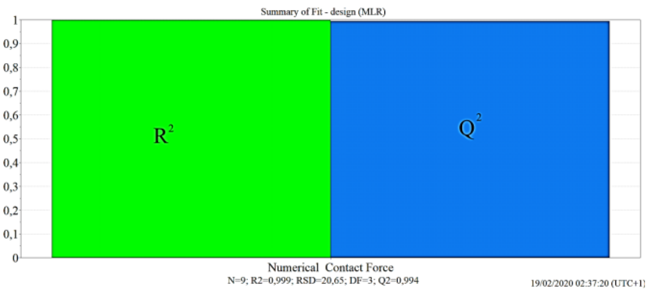


Fig. 6. Descriptive quality of the model

Results shown on Figure.7 gives a good insight on the effect of the factors coefficients of the mathematical model.

It is found that the factor of the height of impact is the most influential (477.2) followed by the mass of absorbed moisture (–108.36). Right after, the registered coefficient in terms of the square of the height of impact relapse to the value of (-51.1), followed in decreasing order by the square of the mass of absorbed water (-147.94) and finally by the combined effect of the height of impact and the mass of water absorbed (4.4). All factors coefficients collected data are reported in Table. 5. The signs of the coefficients are disregarded because the importance is on the absolute values indicating the weight of the coefficients.

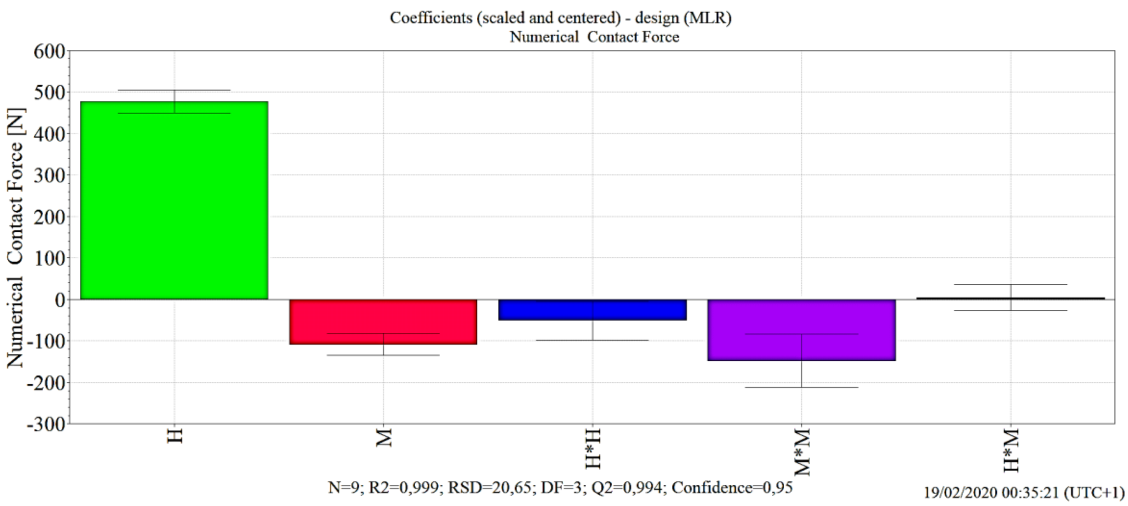


Fig. 7. Factors influencing the contact force.

Table.5.Coefficients of the factors and their interactions.

Numerical Contact Force	Coeff. SC	Coeff. SC	P	Conf. int(±)
Constant	3817,16	19,6753	3,01975e-07	62,616
H	477,189	8,5929	1,28621e-05	27,3466
M	-108,36	8,43227	0,00101697	26,8354
H²	-51,0983	14,6051	0,0395194	46,4803
M²	-147,938	20,2687	0,00531021	64,5043
H×M	4,39473	9,92223	0,687817	31,5771

Finally, the proposed model to predict the contact force and covering both the experimental tests and numerical modelling as function as the height H and the mass of absorbed moisture M in the design space is expressed by:

$$F = 3817{,}16 + 477{,}189H - 108{,}63M + 4{,}39H \times M - 51{,}0983H^2 - 147{,}938M^2 + e \qquad (1.2)$$

III.1.2. GRAFICAL CONTOURS OF THE RESPONSE

The mathematical representation of the function given earlier in Eq. (1.2) is presented in Fig 8. The graphed function shows the contour plots of the response i.e. the response surface corresponding to the contact force as function as the two parameters H and M.

The graphical representation of the model constitutes an important and interesting part of this powerful and judicious DOE method. It reveals that the combined effect of increasing the absorbed moisture and a decrease in the drop height reduces the contact force. The absorbed moisture in this situation gives the material some suppleness (Spongious effect) which results in a decrease in the contact force.

However, it is noticed that after a certain threshold of absorption noticed when $M \in [0.30 - 0.35]\%$ the contact force decreases with the increasing of M for the same applied level of the impact energy. The results of the study are comforted by other investigations [8, 12]. Moisture swelling of the matrix

may alter the state of residual stresses introduced during processing of the composite [5].

On the other hand, the fibber/matrix interface and interlayers region are commonly target by environmental attack, this is generally due to the difficulties in achieving of a perfect chemical bonds between the fibbers and matrix and layers [4, 8 and 10].

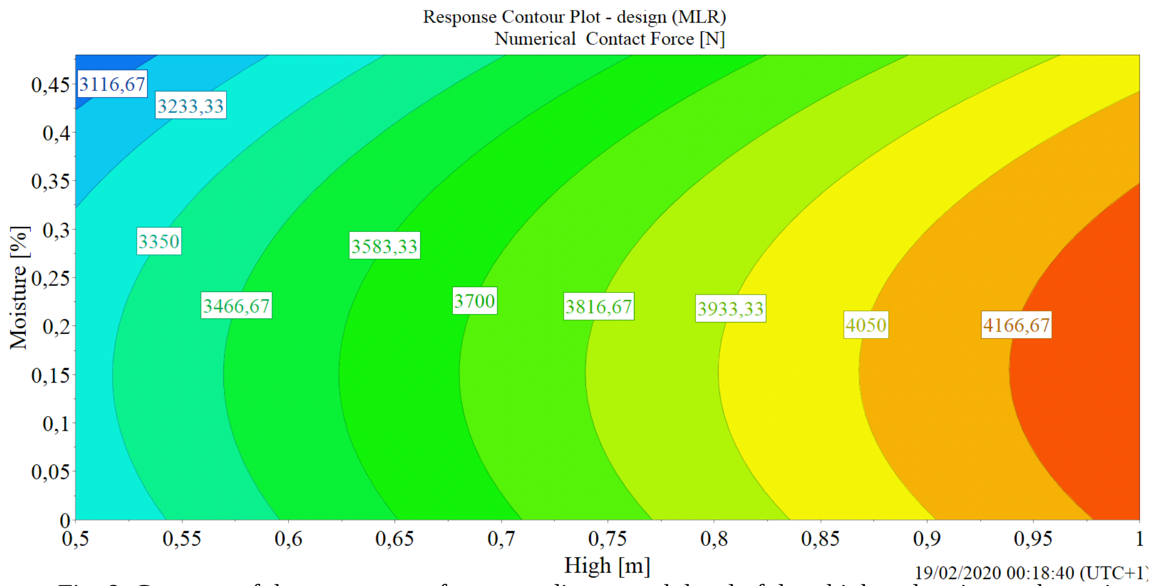


Fig. 8. Contours of the response surface according to each level of drop high and moisture absorptio.

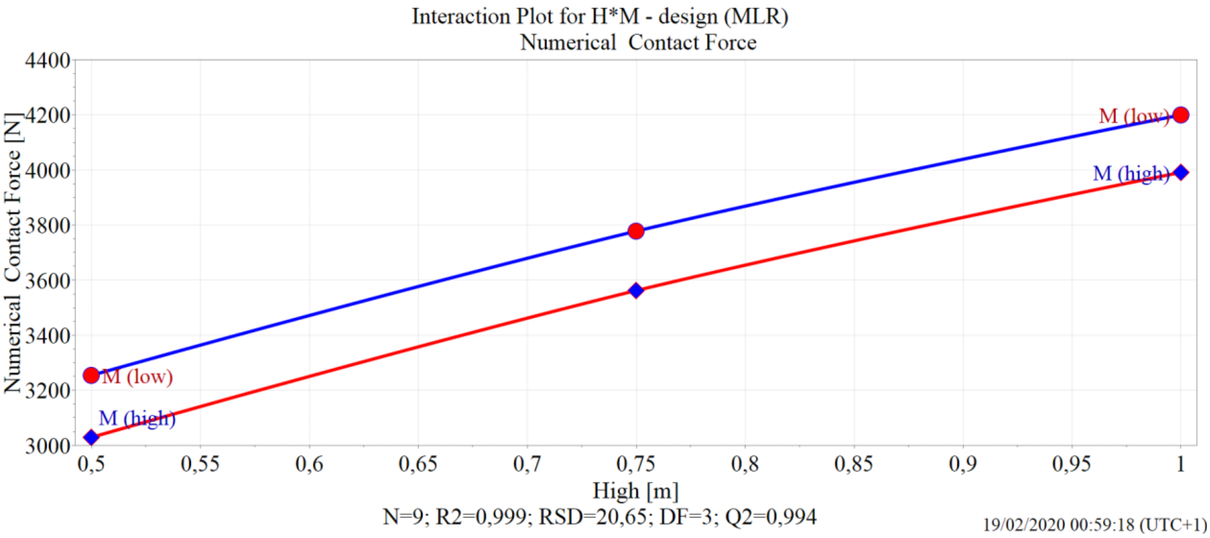
Predicted force:

On Figure.9 the evolution of the predicted force is shown according to each factor. The predictive model gives very close results of the impact force to those obtained numerically and experimentally.

Its observed that when the predicted contact force according to drop height changes is stored, the contact

force present linearly evolution with this last parameter Figure. 9(a). In the other hand, when predicted contact force is registered according to moisture changes the mathematical graph changes on a non-linear shape function.

Case 1: Drop height variation



Case 2: Moisture variation

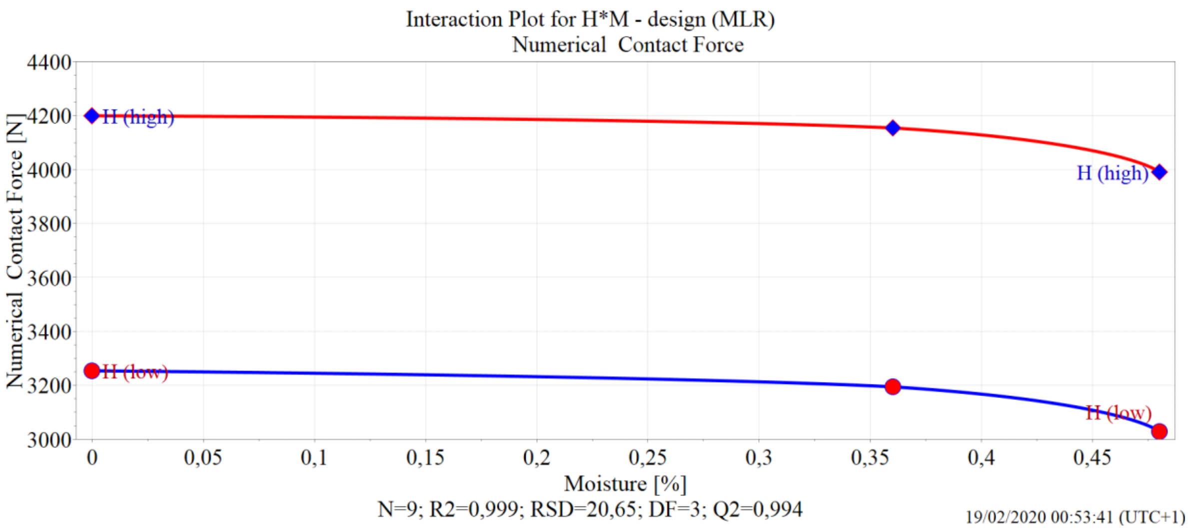


Fig.9. Predicted force as function as the influent parameters (H: case 1; M: case

The computed time history of the contact force acting in the axial direction on the S-

Glass/Polyester plate agrees well with the experimental data in the two studied cases of aged and a non-aged model.

The absorption of the moisture leads to a decrease in contact force which it can represent an interest point.

However, it was seen that after threshold of moisture the contact force decreases with the increasing of M for the same applied level of the impact energy

From the outcome of our investigation on the application of the DOE it is possible to conclude that:

The proposed method permits the establishment of an analytical model of the impact force.

The interaction of the two parameters H and M is illustrated.

REFERENCES

[1] Shrestha, J., et al, Durability of FRP concrete bonds and its constituent properties under the influence of moisture conditions." Journal of Materials in Civil Engineering.(2014).

[2] Mirzaei, G., Mohebby, B., and Ebrahimi, G. (2017). ‘‘Glulam beam made from hydrothermally treated poplar wood with reduced moisture induced stresses,’’ Construction and Building Materials 135, 386-393. DOI: 10.1016/j.conbuildmat.2016.12.178.

[3] Ashraf M. Zenkour , Rabab A. Alghanmi ‘‘Bending of symmetric cross-ply multilayered plates in hygrothermal environments’’. Mathematical Models in Engineering, Vol. 2, Issue 2, 2016, p. 94-107.https://doi.org/10.21595/mme.2016.17405

[4] Tanmoy Bandyopadhyay and Amit Karmakar ‘‘Low-Velocity Impact Response of Delaminated Composite Conical Shells in Hygrothermal Environment due to Time-Delay’’. Procedia Engineering 173 (2017) 463 – 470.11th International Symposium on Plasticity and Impact Mechanics, Implast 2016.

[5] Rongrong Li et al. ‘‘Experimental and Numerical Study of Moisture-induced Stress Formation in Hexagonal Glulam Using X-ray Computed Tomography and Finite-element Analysis’’ BioResources 13(4), 7395-7403. (2018)

[6] Li, Z., Zhang, J., and Sun, Y. “Influence of accelerated aging tests on properties of glued-laminated timber,’’ Journal of Forestry Engineering 29(1), 94-97. DOI: 10.13360/j.issn.1000-8101.2015.01.027.(2015)

[7] Systèmes, D. (2017). "Abaqus 6.17 online documentation." Abaqus User Subroutines Reference Manual.

[8] B.F. Boukhoulda, L. Guillaumat, J.L. Lataillade, E. Adda-Bedia and A. Lousdad. Aging-impact coupling based analysis upon glass/polyester composite material in hygrothermal environment. Materials and design, Vol.32, issue 7, 2011, pp.4080-4087.

[9] User Guide to MODDE By Umetrics Version 5, www.umetrics.com/modde.

[10] K. Zouggar, F.B. Boukhoulda, B. Haddag, M. Nouari. ‘‘Numerical and experimental investigations of S-Glass/Polyester composite laminate plate under low energy impact’’. Composites Part B 89 (2016) 169e186.http://dx.doi.org/10.1016/j.compositesb.2015.11.021

[11] Jacques Goupy. ‘‘Introduction aux plans d'expériences - Organisation des essais et de l'interprétation des résultats’’. 5e édition. Dunod, 416 pages ; ISBN :978-2-10-077802-7

[12] Imielinska K., Guillaumat L., "The effect of water immersion ageing on low-velocity impact behaviour of woven aramid-glass fiber/epoxy composites", Journal of Composites Science and Technology, v. 64, pp.2271-2278. 2004.