Journal of Engineering and Technology for Industrial Applications

ISSN ONLINE: 2447-0228

ITEGAM-JETIA

Manaus, v.11 n.53, p. 65-70. May/June., 2025.

DOI: https://doi.org/10.5935/jetia. v11i53.1532

RESEARCH ARTICLE

OPEN ACCESS

NUMERICAL ANALYSIS OF HYGROTHERMAL EFFECTS ON LOW-VELOCITY IMPACT CONTACT FORCE IN S-GLASS/POLYESTER COMPOSITE PLATES

Mustapha Rabouh[1], Kamel Zouggar[2] and Khelifa Guerraiche[3]

[1] Laboratory of Development in Mechanics and Materials (LDMM) University of Djelfa , Algeria

[2] Laboratory of Mechanics of Structures and Solids (LMSS)Faculty of Technology, Djillali Liabès University of Sidi Bel-Abbès, Algeria.

[3] Mechanical Engineering Department, Faculty of Technology, University of Batna 2, Batna, Algeria NMISSI Laboratory, Faculty of Science and Technology, Biskra University, Biskra, Algeria.

[1]https://orcid.org/0009-0003-2657-0714, [2]https://orcid.org/0000-0001-8495-3754, [3]https://orcid.org/0000-0002-6759-0602

Email: mustapha.rabouh@univ-djelfa.dz, zouggarkamel.zk@gmail.com, guer.khelifa@yahoo.com

ARTICLE INFO

Article History

Received: January 5, 2025

Revised: January 20, 2025

Accepted: May 15, 2025

Published: May 31, 2025

Keywords:

Aged composite

Impact

Design of Experiments (DOE)

Hygrothermal conditions

Numerical simulation.

ABSTRACT

Bonded fiber-reinforced polymer (FRP) composites, particularly CFRP, are widely utilized in structural applications due to their lightweight and sustainable properties. However, their long-term performance is compromised under environmental conditions that introduce moisture and thermal stresses, leading to hygrothermal effects. This study investigates the influence of hygrothermal environments on the contact force of S-glass fiber-reinforced polyester composite plates subjected to low-velocity impact. The research employs finite element modeling using ABAQUS/Explicit to simulate impact behaviors and validate the results against experimental data for aged and non-aged samples. Additionally, a Design of Experiments (DOE) approach is implemented via MODDE 5 software to analyze key parameters and develop a predictive mathematical model. The findings aim to bridge knowledge gaps in understanding the durability and impact response of composite materials in adverse environments, providing insights for structural health monitoring and design optimization.

I. INTRODUCTION

Bonded fiber-reinforced polymer composites (CFRP) have become increasingly popular in various fields, including mechanical and civil engineering, due to their potential for lightweight, sustainable construction solutions, particularly as structural elements like beams and columns [1]. However, CFRP materials face challenges when exposed to environmental factors that introduce moisture and temperature gradients, impacting their long-term performance [2].

Studies have been conducted to assess the behavior of FRP composites under diverse environmental conditions [3],[4]. Despite these efforts, certain harsh environmental impacts on bond durability such as water immersion, high humidity, and freeze-thaw cycles are not yet fully understood [5]. The durability of CFRP under moisture exposure is primarily governed by the rate of water and ion diffusion, as ions rely on water as a transport medium [6]. This diffusion affects the material interfaces, leading to hygrothermal stresses. Moisture absorption at bonded interfaces and within the constituent materials raises the need for a more detailed understanding of its impact. Modeling these diffusion effects has proven challenging, with limited success in translating findings into simulation analyses [7].

Research has recently begun focusing on how environmental parameters impact shock absorption and safety in CFRP for structural health monitoring [8]. The literature highlights a gap in studies on low-velocity impact responses of composites under controlled hygrothermal environments. Impact modeling typically produces contact stresses (impact forces) that may cause matrix cracking or delamination in composite materials [4]. Prolonged exposure to thermal and moisture stresses can further compromise the longevity of these structures.

This study thus focuses on modeling and analyzing the effects of hygrothermal environments on the contact force of S-glass fiber-reinforced polyester composite plates subjected to low-velocity impact, using the finite element software ABAQUS/Explicit. The analysis is divided into two phases: the first phase involves creating a numerical model of low-velocity impact and comparing the results with experimental data on aged and non-aged plates under environmental effects [8]. In the second phase, the numerical results are integrated into MODDE 5 software [9] to establish a Design of Experiments (DOE) framework, identifying key influencing parameters and developing a mathematical model to describe the contact force within the domain under study.

II. NUMERICAL MODELLING PROCEDURES

II.1 MATERIAL

In order to verify the validity of the numerical modeling with the experimental findings presented in [8], a composite plate using C3D8R elements is subjected to low-velocity impact by a projectile with a hemispherical tip. To achieve this, a numerical simulation model is developed using the finite element code ABAQUS/Explicit, which is designed to account for all relevant problem variables, along with the integration of an implemented subroutine (VUMAT) (Figure 1). The S-Glass/Polyester plates are modeled with a stacking sequence of (0°3/90°3) and dimensions of 150×100×4.5mm3. Further details regarding the material structure and modeling techniques can be found in references [8],[10].

The material properties and diffusivity constants along the three primary axes are presented in Table 1. The diffusivities for unidirectional composites are defined as follows:

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

Fibre Vf	3.40000E-01	$^{+}S_1$ (MPa)	1.56060E+03
Thickness (mm)	0.00000E+00	$^{+}S2$ (MPa)	5.49168E+01
E11 (MPa)	3.19141E+04	$^{-}S_1$ (MPa)	-8.32999E+02
E22 (MPa)	6.64106E+03	$^{-}S_2$ (MPa)	-2.69726E+02
E33 (MPa)	6.64106E+03	S_{12} (MPa)	1.12859E+02
G12 (MPa)	2.27120E+03	$^{+}e_1$ (mm/mm)	4.89000E-02
G13 (MPa)	2.27120E+03	$^{+}e_2$ (mm/mm)	8.26928E-03
G23 (MPa)	2.17689E+03	$^{-}e_1$ (mm/mm)	-2.61013E-02
NU12	3.10628E-01	$^{-}e_2$ (mm/mm)	-4.06149E-02
NU13	3.10628E-01	e_{12} (mm/mm)	4.96914E-02
NU23	5.21721E-01	K_1 (W/mm/K)	5.57763E-04
CTE1 (mm/mm/C)	2.48764E-05	K_2 (W/mm/K)	1.66348E-04
CTE2 (mm/mm/C)	2.23585E-04	K_3 (W/mm/K)	1.66348E-04
CTE3 (mm/mm/C)	2.23585E-04	Density (g/mm3)	1.60488E-03
D11=D22=D33 mm2/s,	3.06000 E-12		

Source: Authors, (2025).

$$\begin{cases} D_x = D_{11}\text{: Diffusivity parallel to the fiber direction in a lamina;} \\ D_y = D_{22}\text{: Diffusivity perpendicular to the fiber orientation in a lamina;} \\ D_y = D_{22}\text{: Diffusivity through the thickness of a stacked laminate.} \end{cases}$$

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 Figure.1

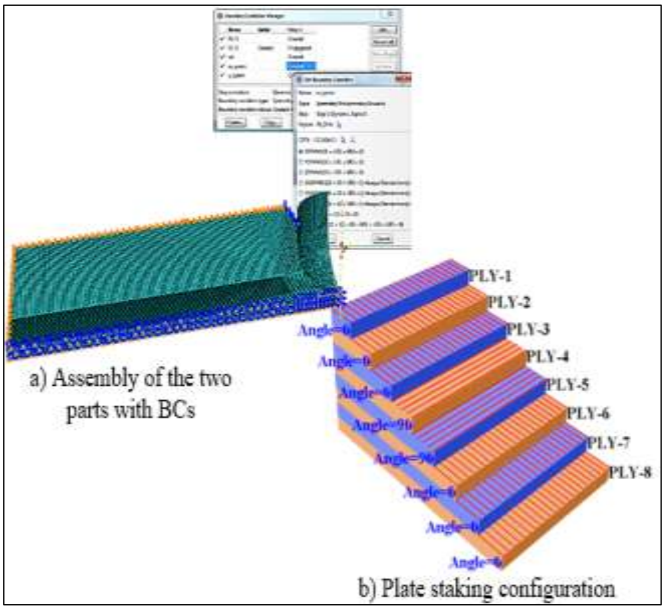

Figure 1: Modelling of the impact test.
Source: Authors, (2025).

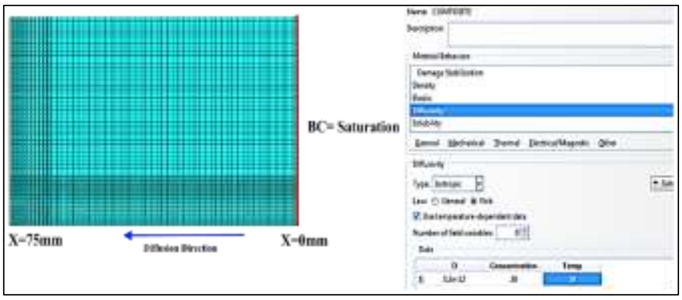

Figure 2: Quarter Model in ABAQUS for Diffusion convergence Analysis.
Source: Authors, (2025).

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.

The modeling approach provides a significant advantage in numerically reproducing experimental tests without time constraints. For instance, the numerical values of F_{IMP}^{Max} in the table correspond to the case of the drop height.

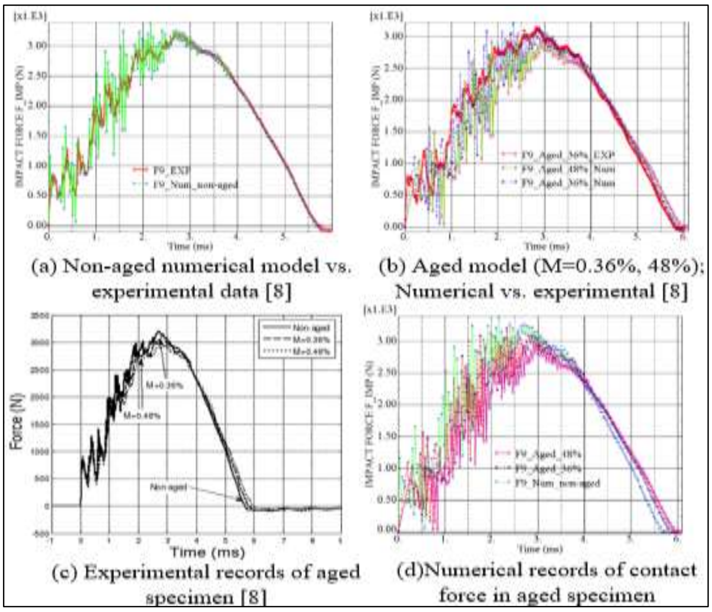

Figure 3: Average Impact Force for 9J energy.
Source: Authors, (2025).

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

H(m)	M(%)	F_{EXP}	F_{Num}	Error
0,5	0	3217	3257	1.24
0,75	0	3730	3772.56	1.14
1,0	0	4171	4201	0.7
0,5	0,36	3140	3181.12	1.31
0,75	0,36	3702	3748.43	1.2
1,0	0,36	//	4146.25	//
0,5	0,48	3002	3039.27	1.2
0,75	0,48	3500	3543.46	1.29
1,0	0.48	//	3997.67	//

Source: Authors, (2025).

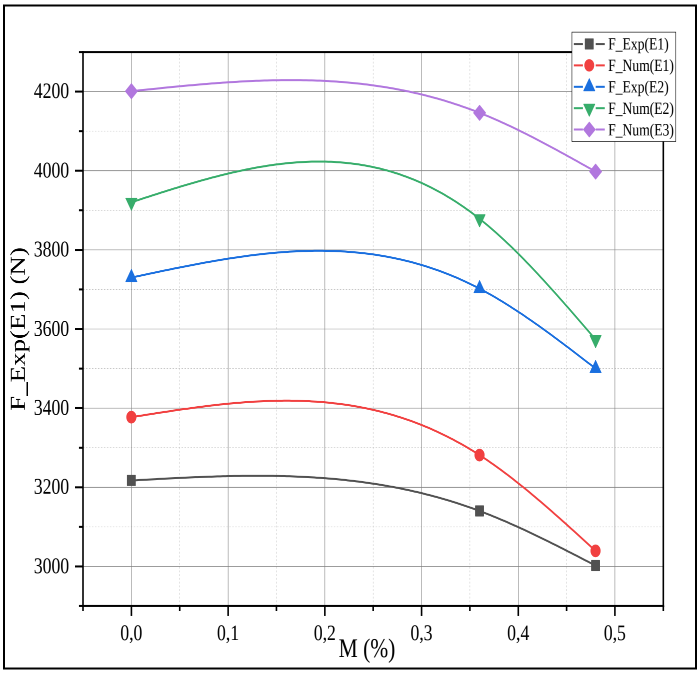

Figure 4: Maximum values of the contact forces as function as the moisture and the energy level.
Source: Authors, (2025).

III. DESIGN OF EXPERIMENTS (DOE) IMPLEMENTATION

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.

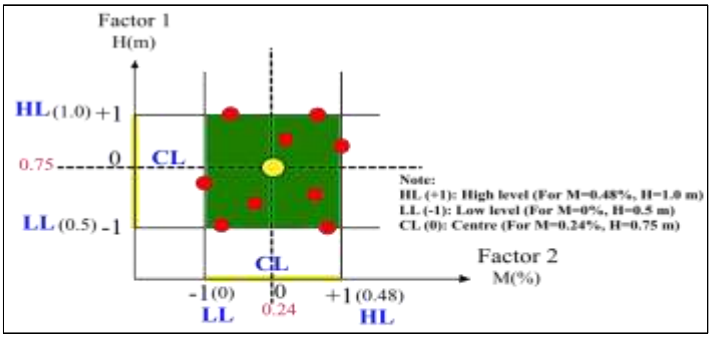

Figure 5: Design space of experiments.
Source: Authors, (2025).

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

Source: Authors, (2025).

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:

$$y = a_0 + a_1x_1 + a_2x_2 + a_{12}x_1x_2 + a_{11}x_1^2 + a_{22}x_2^2 + e \quad (1)$$

The determination of the coefficients $a_0, a_1, a_2x_2, a_{11}, a_{12}$ 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:

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			

Source: Authors, (2025).

- 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 these parameters affect plots for screening designs.

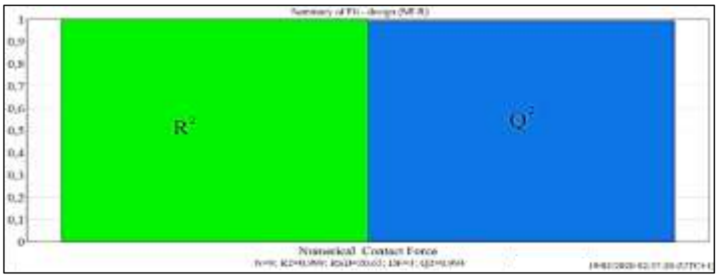

Figure 6: Descriptive quality of the model

- 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.

Table 5: Coefficients of the factors and their interactions.

Numerical Contact Constant	Coeff. SC	Std. Err.	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
H^2	-51,0983	14,6051	0,0395194	46,4803
M^2	-147,938	20,2687	0,00531021	64,5043
M×H	4,39473	9,92223	0,687817	31,5771

Source: Authors, (2025).

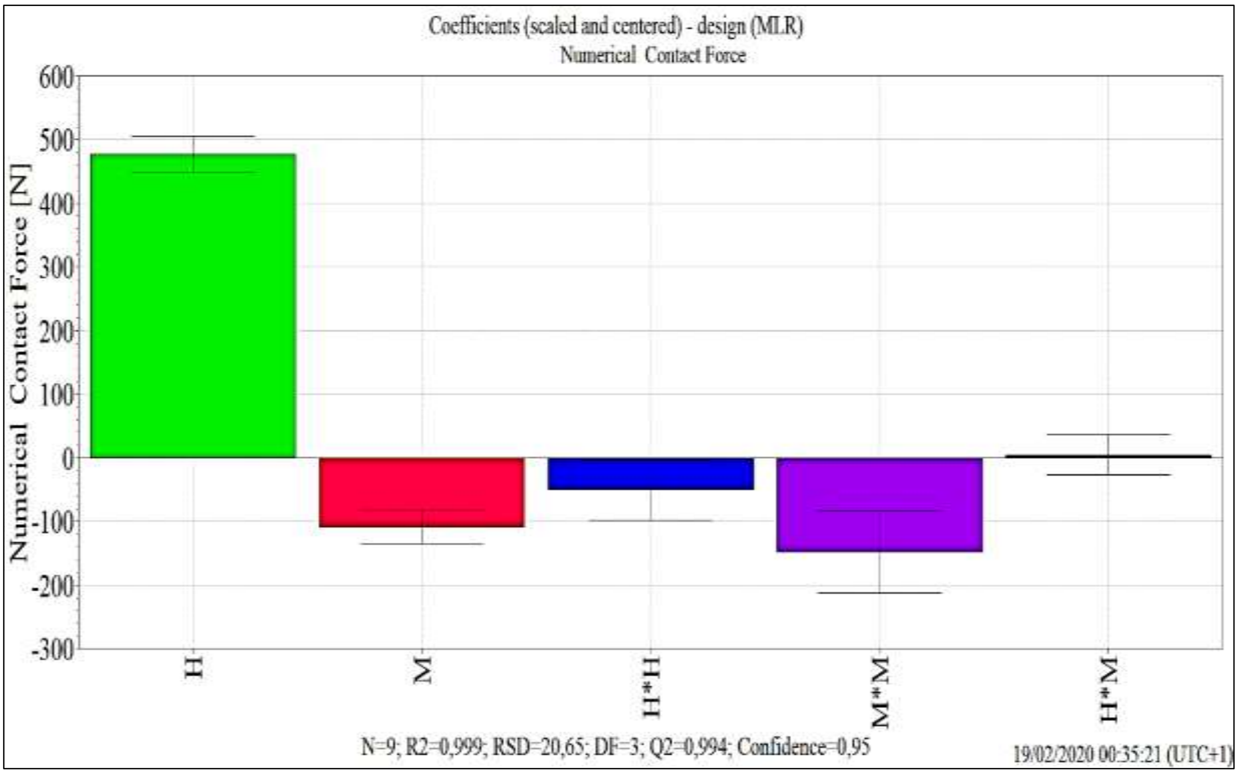

Figure 7: Factors influencing the contact force.
Source: Authors, (2025).

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:

$$F = 3817.16 + 477.189H - 108.36M + 4.39H \times M - 51.0983H^2 - 147.938M^2 + e \quad (2)$$

III. 1.2 GRAFICAL CONTOURS OF THE RESPONSE

- The mathematical representation of the function given earlier in Eq. (2) is presented in Figure 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 bond between the fibbers and matrix and layers [4],[8] and [10].

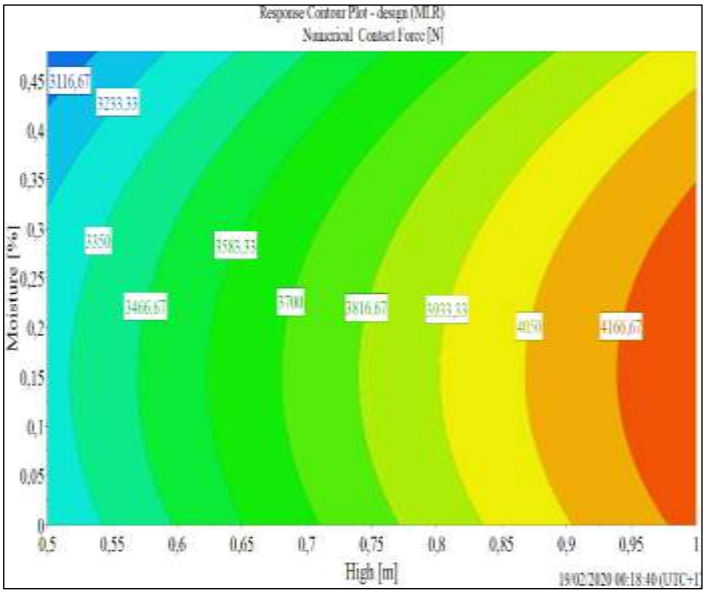

Figure 7: Contours of the response surface according to each level of drop high and moisture absorption.
Source: Authors, (2025).

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.

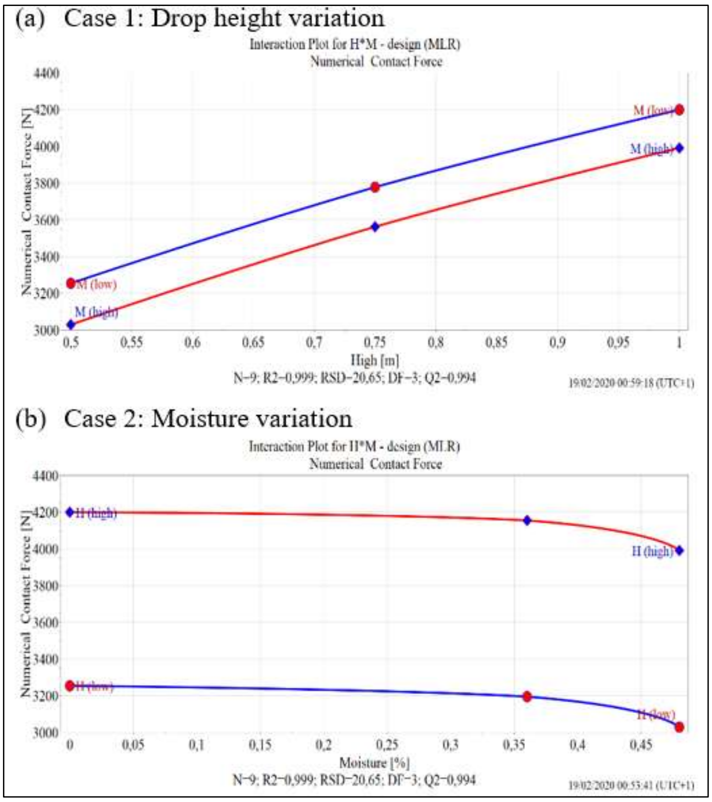

Figure 9: Predicted force as function as the influent parameters (H: case 1; M: case 2).
Source: Authors, (2025).

IV. CONCLUSION

The general conclusions of this study are summarized as follows:

- We have analyzed by the finite element method (FEM) the effect of impact at low energy in S-Glass/Polyester composite laminate.
- 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.
- A predictive model of impact force is exposed.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Kamel Zouggar and Mustapha Rabouh.
Methodology: Mustapha Rabouh and Kamel Zouggar.
Investigation: Mustapha Rabouh and Kamel Zouggar.
Discussion of results: Mustapha Rabouh, Kamel Zouggar and Khelifa Guerraiche.
Writing – Original Draft: Mustapha Rabouh.
Writing – Review and Editing: Kamel Zouggar and Mustapha Rabouh.
Resources: Mustapha Rabouh, Khelifa Guerraiche.
Supervision : Khelifa Guerraiche and Kamel Zouggar.
Approval of the final text: Mustapha Rabouh, Kamel Zouggar and Khelifa Guerraiche.

VI. REFERENCES

[1] J. Shrestha, T. Ueda, and D. Zhang, "Durability of FRP concrete bonds and its constituent properties under the influence of moisture conditions", ASCE, vol. 27, no. 2, pp. 01-13, Jul. 2014. https://doi.org/10.1061/(ASCE)MT.1943-5533.000109

[2] G. Mirzaei, B. Mohebby, and G. Ebrahimi, "Glulam beam made from hydrothermally treated poplar wood with reduced moisture induced stresses", Construction and Building Materials, vol. 135, no. 15, pp. 386-393, March 2017. DOI: 10.1016/j.conbuildmat.2016.12.178 (2017)

[3] M. A. Zenkour, A. R. Alghanmi, "Bending of symmetric cross-ply multilayered plates in hygrothermal environments", MME, Vol. 2, no. 2, pp. 94-107, Dec 2016. https://doi.org/10.21595/mme.2016.17405

[4] T. Bandyopadhyay, A. Karmakar, "Low-Velocity Impact Response of Delaminated Composite Conical Shells in Hygrothermal Environment due to Time-Delay", Procedia Engineering, vol 173, pp 463-470, 11th International Symposium on Plasticity and Impact Mechanics, Implast, 2016. https://doi.org/10.1016/j.proeng.2016.12.064

[5] L. Rongrong et al, "Experimental and Numerical Study of Moisture-induced Stress Formation in Hexagonal Glulam Using X-ray Computed Tomography and Finite-element Analysis", BioResources, vol. 13, no. 4, pp. 7395-7403, Aug 2018. DOI: 10.15376/biores.13.4.7395-7403

[6] Z. Li, J. Zhang, and Y. Sun, "Influence of accelerated aging tests on properties of glued-laminated timber", Journal of Forestry Engineering vol. 29 no. 1, pp. 94-97, 2015. DOI: 10.13360/j.issn.1000-8101.2015.01.027.

[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, no. 7, pp. 4080-4087, Aug 2011. https://doi.org/10.1016/j.matdes.2011.03.009

[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, vol. 89, pp. 169-186, 2015. 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] K. Imielinska, L. Guillaumat, "The effect of water immersion ageing on low-velocity impact behaviour of woven aramid-glass fiber/epoxy composites", Journal of Composites Science and Technology, vol. 64, no13.14, pp.2271-2278, Oct 2004. https://doi.org/10.1016/j.compscitech.2004.03.002.