Journal of Engg. Research Vol. 8 No. (3) September 2020 pp. 153-171

تحديد نقطة عتبة الضرر الناتج عن المواد المركبة باستخدام طريقة تاجوتشي المبنية على الضبابية

***سيدا اربيراك و**إنجين اربيراك**
*قسم الهندسة الصناعية، جامعة اسطنبول جليسيم، اسطنبول، تركيا
**قسم الهندسة الميكانيكية، جامعة بايبورت، بايبورت، تركيا

الخلاصة

تم في هذه الدراسة تحديد نقطة عتبة الضرر الناتج عن تصادم المواد المركبة باستخدام معلمات التصميم المُثلى التي تم الحصول عليها من طريقة تاجوشي المبنية على الضبابية. من المعروف أن طريقتا تاجوشي والضبابية تقدمان الأمثلية لمعلمات التصميم حتى الآن. في طريقة تاجوشي، لا تُعد الأمثلية لمعلمات التصميم كافية لحل مشكلة الأمثلية ذات الاستجابات المتعددة. لذلك، تم دمج نظام المنطق الضبابي مع نظام تاجوشي لحل هذه المشكلة. في هذه الدراسة، تم إجراء تحليل متقدم باستخدام العناصر المنتهية LS-DYNA 3D للكشف عن الأضرار الناتجة عن تأثير السرعة المنخفضة، وتم استخدام معيار ASTM D7136 / D7136M أثناء إجراء تلك التحليلات. كما تم تنفيذ خوارزميات الاتصال لمراقبة أشكال منطقة الضرر بشكل أفضل. علاوة على ذلك، تم ضبط معلمات التحكم (الإنهاء وحساب الفاصل الزمني) لتوفير ارتباط مثالي مع تاريخ القوة – الطاقة – الوقت. وخلصت الدراسة إلى أن طريقة تاجوشي المبنية على أسلوب الضبابية هي أكثر قدرة على تحسين معلمات التصميم التي تتنبأ بنقطة عتبة الضرر الناتج عن تصادم المواد المركبة.

Determination of the Impact Damage Threshold Point of Composite Material Using Fuzzy-Base Taguchi Method

Seda Erbayrak* and Engin Erbayrak**,***

*Department of Industrial Engineering, Istanbul Gelisim University, Istanbul, Turkey
**Department of Mechanical Engineering, Bayburt University, Bayburt, Turkey
*** Corresponding Author: enginerbayrak@bayburt.edu.tr

Submitted: 28/02/2019
Revised: 07/10/2020
Accepted: 15/10/2020

ABSTRACT

In this study, the impact damage threshold point of composite materials was determined using the optimum design parameters obtained from the Fuzzy Based Taguchi Method (FBTM). It is known that both Taguchi and Fuzzy methods provide optimization of design parameters yet, in Taguchi method, optimization of design parameters is not sufficient in solving multi response optimization problem. Therefore, Fuzzy Logic system was combined with the Taguchi system for working out the multi-response optimization problem. In this study, the low velocity impact damage analyses were performed in an LS-DYNA 3D explicit finite element program. ASTM D7136/D7136M standard was used during the low velocity impact analyses. In explicit finite element analyses, contact algorithms were executed to observe better damage zone shapes. Furthermore, the control parameters (termination and computation time step) were tuned to provide perfect correlation with the force-energy-time histories. The study concluded that Fuzzy Based Taguchi Method (FBTM) is much more capable of optimizing the design parameters that predict the impact damage threshold point of the composite material.

Keywords: Low velocity impact, Composite material, Fuzzy Based Taguchi Method (FBTM), Finite element analyses.

INTRODUCTION

Composite materials are composed of two or more different materials possessing mechanical properties higher to those of the individual constituents. Composite materials have better conductivity compared plastics and ceramics. In addition, they have higher strength value in both tension and compression tests. Impact behavior of the composite material is of a major interest among the scientists, since the impact damage in composite material often caused the matrix and fiber failure. It should be stated that the matrix is the one composite component that binds the fiber existing in the composite. The impact analyses of the composite structures can be carried out with different velocity ranges such as low, high, and hyper. However, low velocity impact test is preferred since it generates extended damage within the structure. The low-velocity impact response of composite laminates was considered in a study by Mathivanan and Jerald (2010). They carried out experimental test with a range of impact velocities and concluded that the catastrophic failure occurred in composite laminates due to higher impact velocity. Nguyen *et al*. (2005) presented low velocity impact simulation on sandwich composite structure where experimental and numerical approaches were executed in the study. Their experimental investigation indicated that there is high correlation with the force-time histories in numerical model. Aktay *et al*. (2005) investigated the damage behavior of composite sandwich panels was through the experimental and numerical means where numerical analyses have been implemented in PAM-CRASH finite element program. They pointed out that numerical analysis produced similar conclusions as experimental results (Aktay *et al*, 2005). Farnam *et al*. (2010) studied the low velocity impact behavior of High-performance fiber reinforced cement based composite (HPFRC) composite material. Low velocity impact model was constructed in LS-DYNA finite element program. In their numerical analyses, MAT_SOIL_CONCRETE material type was used to model the composite material. They concluded that HPFRC composite material has higher impact resistance than concrete accordance with the experimental results. Moreover, they also stated that SOIL_CONCRETE material model is suitable for the numerical modeling of concrete subject to low velocity impact. The ballistic impact response of laminated composite panel was investigated in which LS-DYNA finite element program was executed. A parametric study by Gower *et al*. (2008) was considered for determining the material properties in their study. They stated that numerical analyses can determine the velocity of the ballistic impact test. More studies related to the impact damage of composite materials could be examined in the literature; see, for example, Faggiani *et al*. (2010), Hosseinzadeh *et al*. (2006), Aslan *et al*. (2003), and Zhang *et al*. (2006).

There are many methods in the literature for figuring out multi-response optimization problems. However, Fuzzy Based Taguchi Method (FBTM) can be utilized for the multi response optimization in various fields. Sutono *et al*. (2016) used the FBTM to optimize design parameters in multi-response automotive engineering problem. Improving electric discharge machining was studied by Nagaraju *et al*. (2018) using FBTM. Gupta *et al*. (2011) optimized the machining design parameters used in CNC manufacturing processes by FBTM method. The FBTM was proposed to solve the multi-objective problems occurring in drawing dies (Lin and Kuo, 2011). Hsiang *et al*. (2012) studied the multiple performance characteristics index (MPCI) parameters which are existing in FBTM for determining the optimum production methodology of the magnesium alloy. The FBTM was studied to optimize design parameters of a SPM motor. Hwang *et al*. (2013) reported that FBTM, combined with finite element analysis (FEA), provided robust solution for the multi-objective optimization problems.

In our study, the impact damage threshold point of the composite material was determined using the optimum design parameters obtained from Fuzzy Based Taguchi Method (FBTM). The low velocity impact analyses were implemented in a LS-DYNA 3D explicit finite element program. In explicit finite element analyses, contact algorithms were executed to observe better damage zone shapes. Furthermore, the control parameters (termination and computation time step) were tuned to provide perfect correlation with the force-energy-time histories. In optimization section, Fuzzy Logic System was combined with the Taguchi System for working out the multi-response optimization problem.

OPTIMISATION METHODS

Taguchi Method

Taguchi method provides an efficient way for designing processes that improves the quality of products and aids in setting experimental planning. Taguchi method optimization is based on the principle of using the entire design parameters obtained from a small number of experiments. These principles were carried out by utilizing orthogonal arrays (OAs) and signal-to-noise (S/N) ratio. Implementation of this method involves two main steps; OAs are determined corresponding to design points and their levels; then S/N ratio is calculated using orthogonal arrays.

In Taguchi method, three ways are used to analyze the S/N ratio; these are nominal-the-best, larger-the-better, and smaller-the-better.

Nominal-the-best characteristic of S/N ratio can be shown as (Sutono *et al*., 2016)

$$n_{ij} = 10\log\left(\frac{\overline{y_{ij}}^{2}}{s^{2}}\right) \tag{1}$$

Smaller-the-better characteristic of S/N ratio can be written as (Sutono *et al.*, 2016)

$$n_{ij} = -10\log\left(\frac{1}{n}\sum y_{ij}^{2}\right) \tag{2}$$

Larger-the-better characteristic of S/N ratio can be formulated as (Sutono *et al.*, 2016)

$$n_{ij} = -10\log\left(\frac{1}{n}\sum\frac{1}{y_{ij}^{2}}\right) \tag{3}$$

where n_{ij} is the S/N ratio, y_{ij} is the performance value of each design parameter, n is the design parameter, $\overline{y_{ij}}$ is the mean performance, and s^2 is the variance of the performance.

Fuzzy Logic Method

Fuzzy logic is a branch of mathematics that is based on classical logic and generalization of set theory. The architecture of the fuzzy system consists of at least one input and one output variable. Fuzzy logic is distinguished into four parts; Fuzzifier, Knowledge Base, Inference Engine, and Defuzzifier (Figure 1).

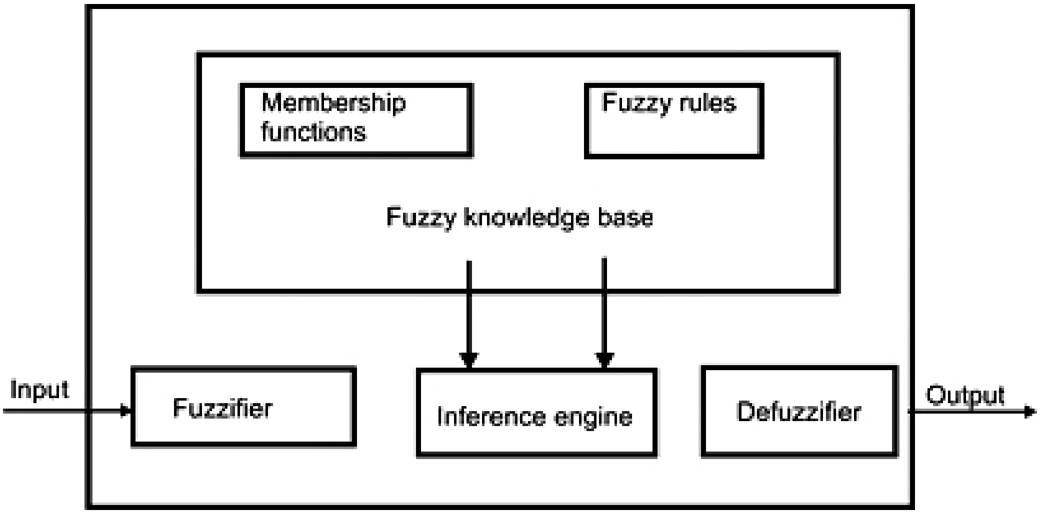

Figure 1. The architecture of the fuzzy system (Nagaraju *et al.*, 2018).

Fuzzifier

The fuzzifier converts crisp input, which includes exact information about the parameter, to fuzzy input. In other words, lengthiness is a parameter containing precise input; however, the fuzzifier converts this precise value to imprecise value such as “long”, “medium” and “small” (Nagaraju *et al.*, 2018).

Knowledge Base

Knowledge base is a part of the fuzzy logic encapsulating the membership functions and fuzzy rules. Membership functions stand for the degree of accuracy in fuzzy logic system. Membership functions can be also explained as the function that works out problems by utilizing the experience rather than theoretical approach. In addition, in fuzzy logic system, the fuzzy rules are used to attain output parameters depending on input variables.

Inference Engine

In fuzzy logic, the inference system is in charge of carrying out inference process on the rules.

Defuzzifier

The basic goal of using the defuzzifier is to convert fuzzy input to crisp input with respect to fuzzy set.

In the last decade, different fuzzy inference systems are used among the scientists. However, Mamdani Fuzzy Model (MFM) is the most popular fuzzy model among the others.

Mamdani Fuzzy Model (MFM)

In fuzzy logic system, Mamdani's method provides compatibility in 'min-max' operations due to its simplicity. Besides its simplicity, Mamdani method yields multi-response output in fuzzy applications. In Mamdani method, many types of fuzzy numbers are used for characterizing the membership functions. The types of fuzzy numbers are monotonic, triangular, trapezoidal, and s-shaped. The triangular fuzzy number was selected to characterize the membership function. The membership function of a triangular fuzzy number is

$$\mu_A(x) = \left\{ \begin{matrix} 0 & x \le a \\ \dfrac{x-a}{c-a} & a \le x \le c \\ \dfrac{b-x}{b-c} & c \le x \le b \\ 0 & x \ge b \end{matrix} \right\} \qquad (4)$$

where μ_A is the membership function of the fuzzy set, x is the variable, and a, b, c are parameters (Sutono *et al*., 2016).

The fuzzy rule is composed of IF-THEN control rules that include multiple inputs and multi-response output. The fuzzy rule can be stated as (Sutono *et al*., 2016);

Rule 1:IF x_1 is A_1 and x_2 B_1 and x_3 is C_1 THEN y is E_1
ELSE
Rule 2: IF x_1 is A_2 and x_2 B_2 and x_3 is C_2 THEN y is E_2
ELSE
....
Rule n: IF x_1 is A_n and x_2 B_n and x_3 is C_n THEN y is E_n

where A_n, B_n, C_n, E_n are fuzzy subset models by corresponding membership functions μ_{An} , μ_{Bn} , μ_{Cn}, μ_{En} respectively (Sutono *et al*., 2016), y is the membership function of the fuzzy multi-response output, and it is defined as

$$\mu_{C0}(y) = \left(\mu_{A1}(x_1) \wedge \mu_{B1}(x_2) \wedge \mu_{C1}(x_3).....\mu_{E1}(y)\right) \vee ...\left(\mu_{An}(x_1) \wedge \mu_{Bn}(x_2) \wedge \mu_{Cn}(x_3) \wedge \mu_{En}(y)\right) \quad (5)$$

where $\wedge$ and $\vee$ are the minimum and maximum indicators. In addition, the non- fuzzy value was considered in this study. The non- fuzzy value is shown as (Sutono *et al.*, 2016)

$$y_0 = \frac{\sum y\mu_{C0}(y)}{\mu_{C0}(y)} \quad (6)$$

The non- fuzzy value is also called the Multiple Performance Characteristics Index (MPCI) (Sutono *et al.*, 2016).

Fuzzy-Based Taguchi Method

In this study, fuzzy logic system was combined with the Taguchi method for the optimization of a design parameter that predicts the impact damage threshold point of the composite material. The process steps of the optimization of Fuzzy-Based Taguchi Method are briefly summarized as follows.

Firstly, the impact damage parameters (i.e., design parameters) were identified for the Taguchi model. Then, convenient Taguchi's orthogonal array was determined in accordance with the number of design parameters and levels. After that, design parameters situated in Taguchi's orthogonal array were assigned to finite element analysis, and S/N ratios were calculated based on finite element analysis data. Subsequently, MPCI was obtained performing fuzzy logic operation on S/N ratios. Eventually, confirmation analyses were carried out over the finite element model to verify the results.

In this study, the process steps of the optimization of FBTM are discussed in the relevant sections to facilitate the monitoring of the article.

DESIGN PARAMETERS OF FINITE ELEMENT ANALYSES

A number of finite element analyses were first reviewed in the literature to determine the appropriate design parameters of the impact behavior of composite material (see, for example, Mathivanan *et al.*, 2010, and Zhang, X.*et al.*, 2006). In general, design parameters of composite material were determined corresponding to the literature. A total of three design parameters that include mass (m) of the impactor, velocity (V) of the impactor, and height (h) of the impactor were assigned to the finite element analysis (FEA).

DETERMINATION OF THE TAGUCHI'S ORTHOGONAL ARRAY

The use of orthogonal arrays (OA) provides the least number of analyses for a given factor. Particularly, in matrix operations, the number of analyses is significantly reduced by using mathematical expressions between orthogonal columns.

The total degree of freedom criterion is used in the selection of orthogonal arrays. The total degree of freedom is the sum of the individual degrees of freedom of all factors in the group. In determination of the orthogonal array, an array equal or greater than the total degree of freedom is selected as the orthogonal array.

In this study, three design parameters were used, and each parameter was set to four levels. In addition, the total degree of freedom was nine. Therefore, the Taguchi L16 OA (Craig, 2012) was utilized. The design table using Taguchi's L16 OA is shown in Table 1.

Table 1. The design table using Taguchi's L16 OA.

#FEA	Parameter h(mm)	Parameter m (kg)	Parameter V (mm/s)
1	0.50	5.00	1.00
2	0.50	10.00	2.00
3	0.50	15.00	3.00
4	0.50	20.00	4.00
5	1.00	5.00	2.00
6	1.00	10.00	1.00
7	1.00	15.00	4.00
8	1.00	20.00	3.00
9	1.50	5.00	3.00
10	1.50	10.00	4.00
11	1.50	15.00	1.00
12	1.50	20.00	2.00
13	2.00	5.00	4.00
14	2.00	10.00	3.00
15	2.00	15.00	2.00
16	2.00	20.00	1.00

THE EXAMPLE OF FINITE ELEMENT ANALYSIS OF IMPACT DAMAGE IN COMPOSITE MATERIAL

Finite Element Analyses for the low velocity impact (LVI) simulations of composite material were executed in LS-DYNA 3D finite element program. In the finite element model, a batch of square, composite plate (100 mm side, 2 mm thickness), and spherical head of impactor with an 8 mm radius were used in accordance with ASTM standard. The fixed-fixed support condition was considered for modeling purposes. In addition, "contact automatic one-way surface to surface" contact algorithms were executed to observe better damage zone shapes (LS-DYNA keyword user's manual, 2007). Termination and computation time steps were defined on LS-DYNA control part. During the analyses, the composite plate was discretized into 20,000 elements and 30,603 nodes; however, the impactor was discretized into 189 elements and 232 nodes.

Carbon/epoxy composite plate was modelled as a unidirectional orthotropic lamina, and steel impactor was modeled linear-elastic-isotropic material in Finite Element Analysis (FEA). The properties of these materials are shown in Table 2 and Table 3 (Vaidyaa and Gautama, 2006).

Table 2. Material properties of the composite plate (Vaidyaa and Gautama, 2006).

Property	Composite Plate
E11 (MPa)	50000
E22 (MPa)	50000
E33 (MPa)	7200
ν21	0.3
ν 31	0.25
ν 32	0.25
G12 (MPa)	5000
G13 (MPa)	3000
G23 (MPa)	3000

Table 3. Material properties of the impactor (Vaidyaa and Gautama, 2006).

Property	Impactor
E (MPa)	210000
ν	0.29

Composite Material Model

In FEA, "MAT-Composite_Damage" (Mat-022) was implemented as a material model for orthotropic characteristics of composite material. The composite material model (Mat-022) is based on the delamination principle of Brewer and Lagace (1988). However, it should be stated here that delamination process in composite material was forecasted by LS-DYNA software due to out-of-plane compression constrains.

The failure predictions in composite plates were carried out using improved failure criteria in FEA. Hou *et al*. (2001) proposed a new criterion for the delamination of composite material:

$$\text{IF } \sigma_{33} \geq 0 \text{ THEN;}$$

$$e_1^{\,2} = \left(\frac{\sigma_{33}}{Z_T}\right)^2 + \frac{\sigma_{23}^{\,2} + \sigma_{13}^{\,2}}{S_{13}^{\,2}(d_{ms}d_{fs} + \delta)} \geq 1 \qquad (7)$$

$$e_1 \geq 1 \quad \text{delamination failure occurs}$$

$$\text{IF } -\sqrt{\left(\sigma_{23}{}^{2}+\sigma_{13}{}^{2}\right)/8} \le \sigma_{33} \le 0 \text{ THEN;}$$
$$e_1{}^{2} = \frac{\sigma_{23}{}^{2}+\sigma_{13}{}^{2}-8\sigma_{33}{}^{2}}{S_{13}{}^{2}(d_{ms}d_{fs}+\delta)} \ge 1 \tag{8}$$

$$\text{IF } \sigma_{33} \le -\sqrt{\left(\sigma_{23}{}^{2}+\sigma_{13}{}^{2}\right)/8} \text{ THEN;}$$
$$e_1{}^{2} \equiv 0 \tag{9}$$

where e_1 is the delamination indictor, δ is the displacement value of composite material, σ_{33} is stress in the through-thickness direction, σ_{23} is shear stress in the through-thickness direction, σ_{31} is shear stress in the fiber directions, Z_T is tensile strength in the through-thickness direction, S_{13} is shear strength in the fiber directions, d_{ms} is matrix damage coefficient, and d_{fs} is fiber damage coefficient (Hou *et al.*, 2001). Matrix and fiber damage coefficients are equal to 1 when the composite plate is not damaged. In addition, the displacement value of composite material is equal to 0 when the matrix and fiber damage coefficients are equal to 1.

Evaluation of Finite Element Analysis (FEA)

The FEA was implemented in accordance with the Taguchi's L16 OA. A total of sixteen finite element analyzes were performed using three design parameters and levels. As mentioned in the previous section, the three design parameters were assigned in LS-DYNA as input parameters. Failure Energy and Reaction Force, obtained from in LS-DYNA, were used as the output parameters. The Failure Energy is defined as the energy absorbed by composite material during the impact. Reaction Force is used to determine the forces of the slave and master sides of each contact interface. Because of using two output parameters, in the optimization part, this problem was evaluated as multiple response optimization problems.

At this point, it should be stated that friction energy was not taken into account for obtaining the output parameter.

The results of Failure Energy and Reaction Force of each design parameters are given in Table 4.

Table 4. The results of failure energy and reaction force of each design parameters.

#FEA	Failure Energy (J)	Reaction Force (N)
1	2.07	148.40
2	16.14	447.00
3	46.30	813.50
4	102.08	1163.75
5	8.29	318.50
6	4.12	215.62
7	61.57	1081.62
8	84.20	959.8
9	18.47	483.15
10	54.12	898.27
11	4.71	229.39
12	29.60	630.31
13	31.11	655.89
14	34.86	703.50
15	24.75	568.54
16	5.31	246.48

The Reaction Force and Failure Energy plots obtained from LS-DYNA were shown in Figure 2.

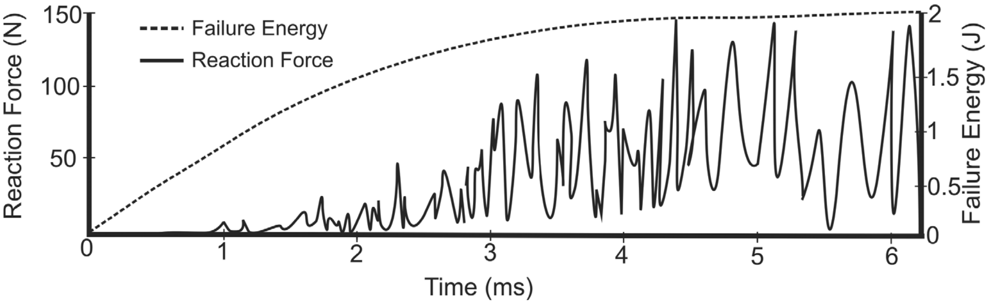

Figure 2. The reaction force and failure energy plots (#FEA 1).

In Figure 2, the diagram of Failure Energy and Reaction Force was plotted by using the first design parameter, and it was controlled so that the obtained results were consistent with the literature (Liang *et al*, 2015). The plots related to other design parameters, not reported herein for the sake of brevity, showed a similar behavior with different values.

The failure deformation of composites for each design parameter was illustrated in Figure 3.

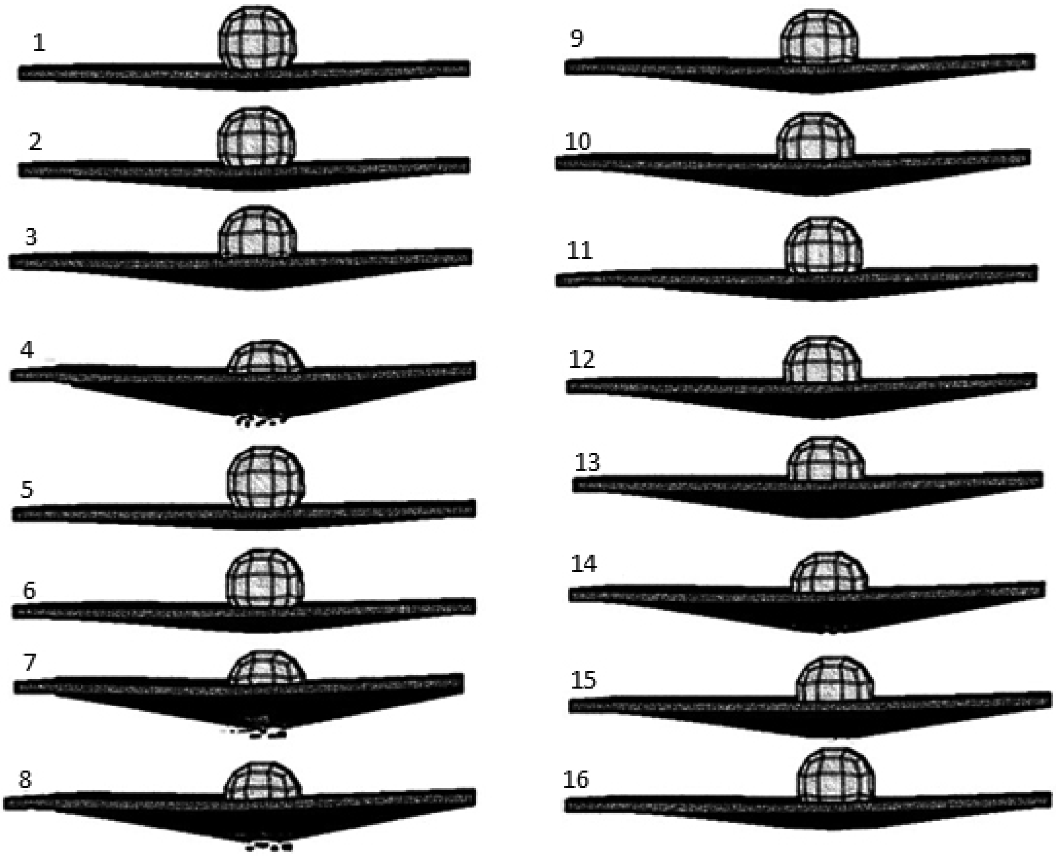

Figure 3. The failure deformation composites for each design parameter.

As seen in Figure 3, the composite plate was either damaged or not deformed significantly. Disintegration portions of the composite material are seen in the analysis numbers 4,7, and 8. In addition, similar results were determined using delamination criteria of composite material. These results interpreted as the optimizations of design parameters in Taguchi method are not capable of predicting the impact damage threshold point of the composite material. To overcome this difficulty, fuzzy logic system was combined with the Taguchi model.

DETERMINATION OF THE MULTIPLE PERFORMANCE CHARACTERISTICS INDEX (MPCI)

In Fuzzy Based Taguchi Method, firstly, S/N ratios are defined as an input parameter, then the MPCI value is obtained in accordance with fuzzy inference rules (see Equation (6)).

The steps of determining the MPCI are briefly summarized. Initially, larger-the-better characteristic of S/N ratio (see Equation (3)) is calculated by using the result of Failure Energy and Reaction Force for each design parameter. The value of S/N ratio was given in Table 5.

Table 5. The values of S/N ratio.

#FEA	Failure Energy (J)	Reaction Force (N)	S/N (Energy)	S/N (Force)
1	2.07	148.40	6.340362021	43.42867802
2	16.14	447.00	24.15807061	53.00615046
3	46.30	813.50	33.31161982	58.20715115
4	102.08	1163.75	40.17881323	61.31719388
5	8.29	318.50	18.37109061	50.06218873
6	4.12	215.62	12.29794432	46.67378083
7	61.57	1081.62	35.78738307	60.68149418
8	84.20	959.8	38.50624183	59.64361491
9	18.47	483.15	25.32933791	53.68163968
10	54.12	898.27	34.66779771	59.06813791
11	4.71	229.39	13.46041814	47.21148963
12	29.60	630.31	29.42583422	55.99108395
13	31.11	655.89	29.85800022	56.33662019
14	34.86	703.50	30.84654766	56.94528204
15	24.75	568.54	27.87150407	55.09522050
16	5.31	246.48	14.50189042	47.83563371

Then, S/N ratios were inserted as input parameters into the fuzzy logic toolbox of the MATLAB software. After that, triangular membership function was defined, and both input and output parameters were distinguished into linguistic fuzzy subsets. The input parameter consisted of three membership functions bearing fuzzy numbers small (S), medium (M), and large (L), and the output parameter consisted of five membership functions bearing fuzzy numbers, that is very small (VS), small, medium, large, and very large (VL). Fuzzy logic model designed in MATLAB is shown in Figure 4.

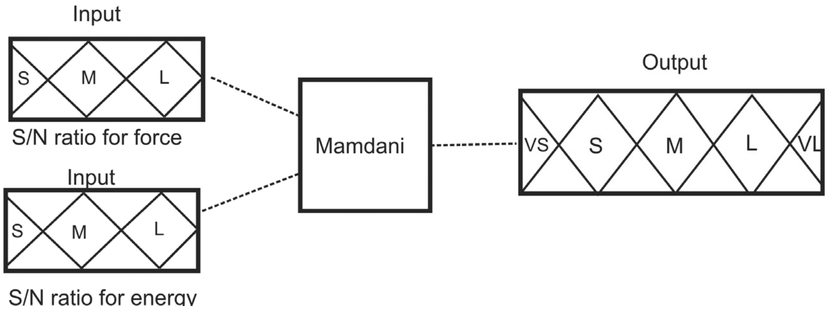

Figure 4. Fuzzy logic model.

Before the fuzzy model was executed in MATLAB, the fuzzy rules were constructed. At first, the number of fuzzy rules was determined. Because there are two fuzzy inputs and each input has three fuzzy subsets, the nine rules were calculated ($3^2 = 9$). As mentioned in the optimization section, the fuzzy rule is composed of a group of IF-THEN control rules. Therefore, the nine fuzzy rules were constituted in accordance with the IF-THEN rule.

The fuzzy rules are as follows:

Rule 1: Failure energy is Small and Reaction force is Small Then MPCI is Very Small

Else

Rule 2: Failure energy is Small and Reaction force is Medium Then MPCI is Small

Else

Rule 3: Failure energy is Small and Reaction force is Large Then MPCI is Medium

Else

Rule 4: Failure energy is Medium and Reaction force is Small Then MPCI is Small

Else

Rule 5: Failure energy is Medium and Reaction force is Medium Then MPCI is Medium

Else

Rule 6: Failure energy is Medium and Reaction force is Large Then MPCI is Large

Else

Rule 7: Failure energy is Large and Reaction force is Small Then MPCI is Medium

Else

Rule 8: Failure energy is Large and Reaction force is Medium Then MPCI is Large

Else

Rule 9: Failure energy is Large and Reaction force is Large Then MPCI is Very Large

After these fuzzy rules were assigned in MATLAB, the membership function of a fuzzy multi-response was appropriately determined to Mamdani Fuzzy Model (see Equation (5)). Lastly, the MPCI values were calculated by the defuzzifier in fuzzy model (see Equation (6)), and it was illustrated as an output parameter. Additionally, it is known that, in fuzzy logic system, MPCI is always obtained as a single output value regardless of the number of input parameters (Figure 4). The MPCI results are presented in Table 6.

Table 6. The values of MPCI.

#FEA	S/N (Energy)	S/N (Force)	MPCI
1	6.340362021	43.42867802	0.08
2	24.15807061	53.00615046	0.538
3	33.31161982	58.20715115	0.687
4	40.17881323	61.31719388	0.920
5	18.37109061	50.06218873	0.408
6	12.29794432	46.67378083	0.309
7	35.78738307	60.68149418	0.763
8	38.50624183	59.64361491	0.771
9	25.32933791	53.68163968	0.542
10	34.66779771	59.06813791	0.718
11	13.46041814	47.21148963	0.328
12	29.42583422	55.99108395	0.613
13	29.85800022	56.33662019	0.633
14	30.84654766	56.94528204	0.639
15	27.87150407	55.09522050	0.601
16	14.50189042	47.83563371	0.334

It is visible from Table 6 that MPCI value is taking the higher value when the S/N ratio results have the higher value. It can be interpreted that higher S/N ratio provides the higher multiple performance characteristics index.

The confirmation test was performed as the last procedure of the FBTM method. The goal of the confirmation test was to verify to predict the threshold point of impact damage in composite material. Before the confirmation test, the mean MPCI values were calculated according to the levels of each parameter. These values are given in Table 7.

Table 7. Mean MPCI values for each level of design parameters.

	Level 1	Level 2	Level 3	Level 4
Parameter h (mm)	0.55625	0.56275	0.55025	0.55175
Parameter m (kg)	0.41575	0.55100	0.59475	0.6595
ParameterV (mm/s)	0.26275	0.5400	0.65975	0.7585

After that, the highest mean MPCI values were determined in Table 7. It is known that higher mean MPCI values provide higher product quality (Ramaiah *et al*., 2013). Therefore, the highest mean MPCI values were used during the confirmation test. In Table 7, the design parameters with the highest level are the impactor height at level-2 (1 mm), the impactor mass at level-4 (20 kg), and the impactor velocity at level-4 (4mm/s). Eventually, the confirmation test was executed.

CONFIRMATION TEST

In the confirmation test, the highest level of the design parameters was obtained in Table 7, which was used to verify the threshold point of impact damage in composite material in LS-DYNA finite element program. The main purpose of considering the stress distribution on impact point is to control the criterion of delamination of the composite material (see Equation (7)). Stresses at the tip of the impact were used in Equation (7), and the delamination indictor was determined. It was observed that delamination indictor was close to 1 (see Appendix). In addition, the Failure Energy and Reaction Force were obtained as 59.27 J and 980.50 N, respectively. Above these values, delamination failure was seen in numerical analyses (see Figure 3 and Table 4). As a result, it could be interpreted that the design parameters with the highest level are capable of predicting the impact damage threshold point of the composite material.

CONCLUSIONS

In this study, the impact damage threshold point of the composite material was determined using optimum design parameters obtained from Fuzzy-Based Taguchi Method (FBTM). The impact damage model was implemented in a LS-DYNA 3D explicit finite element program to simulate the multi-response of damage in composite material. The main conclusions are as follows:

1. In using Taguchi methods, optimization of design parameters is not capable of predicting the impact damage threshold point of the composite material.
2. Equations of the delamination criteria of composite material proposed by Hou *et al*., 2001, were taken into account for determining the impact damage threshold point. It was seen that the determination of the impact damage threshold for composite materials, considering finite elements results alone, may not be conclusive. For example, optimum mesh size, contact type, and the material models used in finite element analyses influence the impact energy of the composite material directly. If any of these parameters are incorrectly determined, the finite element analysis results will be inaccurate. Therefore, finite element analysis results are compared with theoretical results for obtaining accurate results.

3. The confirmation test for Taguchi's method was carried out with highest mean MPCI values of the design parameters obtained from Fuzzy Based Taguchi Method (FBTM) because optimization of design parameters used in Taguchi Method is not capable of predicting the impact damage threshold point of the composite material (see figure 3). After the confirmation test, the threshold impact energy and reaction force were obtained as 59.27 J and 980.5 N, respectively. Above these values, delamination failure was observed in both numerical analyses and delamination criteria approach. Therefore, these values were interpreted as threshold values. It was concluded that FBTM is much more capable of optimizing the design parameters that predict the impact damage threshold point of the composite material.

4. We believe that this study makes significant contribution to the existing literature. In this study, impact damage threshold point of composite material was determined by using optimization and material delamination criteria without the need for experimental investigation. It is known that experimental studies have disadvantages as well as advantages. For instance, the results obtained from the experimental study may not be accurate due to possible human errors. In addition, experimental work is a time-consuming process. Moreover, external variables (environmental conditions, device calibration, etc.) may not always be controlled. Therefore, it is thought that it is important to determine threshold values of composite materials without the need for experimental investigation.

REFERENCES

Mathivanan, R.N. & Jerald, J. 2010. Experimental ınvestigation of woven e-glass epoxy composite laminates subjected to low-velocity ımpact at different energy levels**.** The Journal of Minerals and Materials Characterization and Engineering. 9(7) : 643-652.

Nguyen, M.Q., Jacombs, S.S., Thomson, R.S., Hachenberg, D. & Scott, M.L. 2005. Simulation of impact on sandwich structures. Composite Structure. 67(2): 217–227.

Aktay, L., Johnson, A.F. & Holzapfel, M. 2005. Prediction of impact damage on sandwich composite panels. Computational Materials Science. 32(3-4): 252–260.

Farnam, Y., Mohammadi, S. & Shekarchi, M. 2010. Experimental and numerical investigations of low velocity impact behavior of high-performance fiber-reinforced cement based composite. International Journal of Impact Engineering. 37(2): 220–229.

Gower, H.L., Cronin, D.S. & Plumtree, A. 2008. Ballistic impact response of laminated composite panels. International Journal of Impact Engineering. 35(9) : 1000–1008.

Faggiani, A. & Falzon, B.G. 2010. Predicting low-velocity impact damage on a stiffened composite panel. Composites Part A. 41(6): 737–749.

Hosseinzadeh, R., Shokrieh, M.M. & Lessard, L. 2006. Damage behavior of fiber reinforced composite plates subjected to drop weight impacts. Composite Science and Technology.66(1): 61–68.

Aslan, Z., Karakuzu, R. & Okutan, B. 2003. The response of laminated composite plates under low-velocity impact loading. Composite Structure.59(1): 119–127.

Zhang, X., Hounslow, L. & Grassi, M. 2006. Improvement of low-velocity impact and compression-after-impact performance by z-fibre pinning. Composite Science and Technology. 66(15) :2785–2794.

Sutono, S. B., Abdul-Rashid, S. H., Aoyama, H. & Taha, Z. 2016. Fuzzy-based taguchi method for multi-response optimization of product form design in kansei engineering: a case study on car form design. Journal of Advanced Mechanical Design, Systems and Manufacturing. 10(9): 1-16.

Nagaraju, N., Venkatesu, S. & Ujwala, N.G. 2018. Optimization of Process Parameters of EDM Process Using Fuzzy Logic and Taguchi Methods for Improving Material Removal Rate and Surface Finish. Materials Today: Proceedings.5(2): 7420–7428.

Gupta, A., Singh, H. & Aggarwal, A. 2011. Taguchi-fuzzy multi output optimization (MOO) in high speed CNC turning of AISI

P-20 tool steel. Expert Systems with Applications. 38(6): 6822–6828.

Lin B. T. & Kuo, C. C. 2011. Application of the fuzzy-based taguchi method for the structural design of drawing dies. International Journal of Advanced Manufacturing Technology. 55(1–4): 83–93.

Hsiang, S. H., Lin, Y. W. & Lai, J. W. 2012. Application of fuzzy-based taguchi method to the optimization of extrusion of magnesium alloy bicycle carriers. Journal of Intelligent Manufacturing. 23(3): 629–638.

Hwang, C.C., Chang, C. M. & Liu, C. T. 2013. A fuzzy-based taguchi method for multi objective design of PM motors. IEEE Transactions on Magnetics. 49(5): 2153 – 2156.

Nostrand, R.C.V. 2012. Design of experiments using the taguchi approach: 16 steps to product and process improvement. Technometrics. 44(3): 289.

LS-DYNA keyword user's manual, version 971., Livermore, CA: Livermore Software Technology Corporation; 2007.

Vaidyaa, U. K., Gautama, A.R.S., Hosurb, M. & Duttac, P. 2006. Experimental–numerical studies of transverse impact response of adhesively bonded lap joints in composite structures. International Journal of Adhesion and Adhesive. 26(3): 184–198.

Brewer, J.C. & Lagace, P. A. 1988. Quadratic stress criterion for initiation of delamination. Journal of Composite Material. 22(1): 1141-1155.

Hou, J.P., Petrinic, N. & Ruiz, C. 2001. A delamination criterion for laminated composites under low-velocity impact. Composite Science and Technology. 61(14) : 2069–2074.

Ramaiah, P.V., Rajesh, N. & Reddy, K. D. 2013. Determination of optimum influential parameters in turning of Al6061 using fuzzy logic. International Journal of Innovative Research in Science Engineering and Technology.2(10) : 5555-5560.

Liang, S., Guillaumat, L.& Gning, P. B. 2015. Impact behaviour of flax/epoxy composite plates. International Journal of Impact Engineering. 80(1) :56-64.

APPENDIX

1. The delamination indicator was calculated in accordance with ‘Equation 7’. Firstly, the stresses that occurred around impact damage were determined as shown in Figure A. (All stress units are in MPa.)

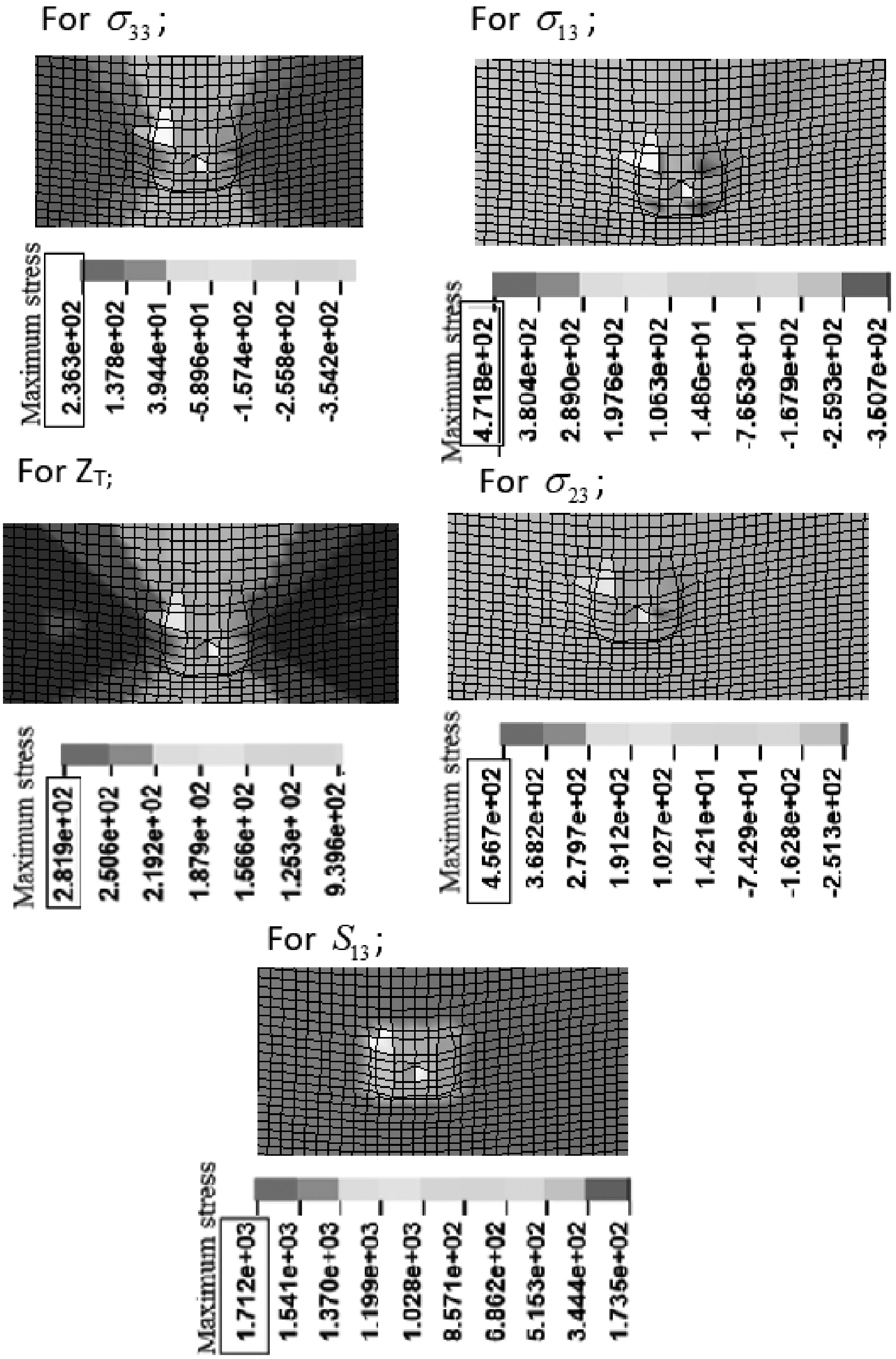

Figure A. Different stress distributions at the impact point.

2. These maximum stress values were substituted in ‘Equation 7’, and the delamination indicator was calculated.

$$e_1^{\,2} = \left(\frac{236.3}{281.9}\right)^2 + \frac{456.7^2 + 471.8^2}{1712^2(0+1)} \qquad \text{(A1)}$$

$$e_1 = 0.8497$$