


## Evaluation of Adhesive Materials Used in Wind Turbine Blades

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### Abstract

Adhesives bonds which are used extensively in the joining of FRP elements in wind turbine are considered a strong potential to replace the bolted joints found in most commercial aircraft. In this paper, a new method which is based on the integration of a Fuzzy Normalized-Hamming distance and Ideal Alternative (FL<sub>2</sub>DIA) model is proposed for the holistic evaluation of the different families of adhesive materials, which can be used for the formation of joints in mechanical systems and for joining wind turbine blades. The adhesive materials which are evaluated with respect to the fracture mechanics-based criteria use expert-based opinion to select the best alternative. The result from the study shows that Acrylic adhesive material (A<sub>3</sub>) has the highest potential to be used for joining wind turbine blade and for the formation of joints in commercial aircraft. The study conclude that the procedure described for the evaluation of the adhesive material has led to the selection of the best structural adhesive to bond the FRP wind turbine blade. Also, it has revealed the suitability, rationality, and feasibility of using the proposed method for ranking the different alternatives as the result from the study have been fully compared with similar existing method (traditional fuzzy TOPSIS model) under the same condition. The comparison result which focuses on the ranking of the adhesive material shows total agreement with the proposed method.

**Keywords:** Adhesives bonds; wind turbine blade; Fuzzy Normalized-Hamming distance and Ideal Alternative (FL<sub>2</sub>DIA) model; Fibre Reinforced Plastic (FRP)

### Rüzgar Türbini Kanatlarında Kullanılan Yapıştırıcı Malzemelerin Değerlendirilmesi

#### Öz

Rüzgar türbinindeki FRP elemanlarının birleştirilmesinde yaygın olarak kullanılan yapıştırıcı bağların, çoğu ticari uçakta bulunan civatalı bağlantıların yerine geçmek için güçlü bir potansiyeli olduğu düşünülmektedir. Bu makalede, mekanik sistemlerde mafsal (bağlantı) oluşumu ve rüzgar türbini kanatlarının birleştirilmesi için kullanılabilecek yapıştırıcı malzemelerin farklı ailelerinin bütünsel değerlendirilmesi için Bulanık Normalize edilmiş-Hamming (sinyal) aralığı ve İdeal Alternatif (FL<sub>2</sub>DIA) modelinin entegrasyonuna dayanan yeni bir yöntem önerilmiştir. Kırılma mekaniği temelli kriterlere göre değerlendirilen yapıştırıcı malzemelerde, en iyi alternatifi seçmek için uzman temelli görüş kullanır. Çalışmanın sonucu, Akrilik yapıştırıcı malzemenin (A<sub>3</sub>), rüzgar türbini kanadının birleştirilmesi ve ticari uçaklarda mafsal oluşumu için en yüksek potansiyele sahip olduğunu göstermektedir. Çalışma sonucu, yapıştırıcı malzemenin değerlendirilmesi için tanımlanan prosedür, FRP rüzgar türbini kanadının yapıştırılması için en iyi yapısal yapıştırıcının seçimine yol açmıştır. Ayrıca, aynı şart altında benzer mevcut yöntem (geleneksel bulanık TOPSIS modeli) ile tamamen karşılaştırılan çalışma, farklı alternatifleri sıralamak için önerilen yöntemi kullanmanın uygunluğu, rasyonitesi ve fizibilitesini ortaya çıkarmıştır. Yapıştırıcı malzemenin sıralamasına odaklanan karşılaştırma sonucu, önerilen yöntemle tam uyumu göstermiştir.

**Anahtar Kelimeler:** Yapıştırıcı bağlar; Rüzgar türbini kanadı; Bulanık Normalize edilmiş-Hamming aralığı ve İdeal Alternatif (FL<sub>2</sub>DIA) modeli; Elyaf Takviyeli Plastik (FRP)

## 1. Introduction

The attractive physical and mechanical properties of Fibre Reinforced Plastic (FRP) particularly its high strength and stiffness to weight characteristic has made it one of the most sorts after material for engineering designs. And has led to it increasing “Green” application (Mohammed, et al., 2015). Encouraged by these outstanding properties, the next generation of the Boeing 787 Dreamliner will have 50% of its structural element made of FRP. This is basically to help reduce the weight of the aircraft and minimize its fuel consumption and corresponding engine emissions (Milberg, 2015; Nicolais, et al., 2011). Also, the blades used in all most all the modern megawatt wind turbines systems designs are made from the FRP which have drastically reduced the inertia of the turbine system, thus improving its ability to harvest more energy from dynamic winds (Mishnaevsky et al., 2017; Schubel & Crossley, 2012).

To fully take advantage and control of this material for the design and used for so many other engineering purposes, a suitable joining method is required. There are basically three existing methods for joining FRP materials, that is a bolting method, self-piercing rivet method and the use of adhesive bonding method (Oltean, et al., 2009). Several research study of bolt joining method for FRP materials have been conducted, the studies however all concluded that the bolting method is not suitable for joining FRP materials, most especially when used in complex designs like aircraft or wind turbine systems (Hollaway, 2011; Kelly, 2004; Khani, 2015). The following reasons however, have been put forward for such conclusion;

- (1) The bolt joining method is capable of introducing structural discontinuity (stress raiser) which can result in fiber breakage and holes in the FRP material;
- (2) The introduction of unwanted weight increase that diminishes the key reason for using FRP material in the first place; and
- (3) The protruded bolt heads and nuts increase the aerodynamic drag of the assembly.

For the self-piercing rivet method and the adhesive bonding techniques, the research studies that have been conducted and the practitioners opinions gathered on the joining of FRP materials, all concluded that, none of the above-listed problems are recorded when they are joined. Also, the following economic advantages of the methods are listed as;

- (1) Ease to design for flexibility and assembly in applications and
- (2) Good aerodynamic characteristics which are critical for systems like megawatt wind turbine (Kroll et al., 2011).

Adhesives bonds which are used extensively in the joining of FRP elements in wind turbine system, are considered a strong potential to replace the bolted joints found in most of the commercial aircraft (Halliwell, 2012). With adhesive bonds in commercial aircraft, about 50% of the joint weight in the structure is bound to reduce. The adhesive bonds are formed by means of surface attachments; the reliability of these attachments is of critical importance to the design and manufacturing of their joints. Despite the many advantages of the application of adhesive bonding, it is still difficult to design, analyze and optimize adhesive bonded joints in mechanical systems (LeBacq, et al., 2002). Hence, the call for

more research on the selection of suitable adhesive bond/family, from the long list of adhesives available for the formation of joints in mechanical system. As well as, research on the design, analysis and evaluation of structural adhesive joints types for enhancing the performance and understanding of structural behavior (Arenas, et al., 2012) in complex mechanical systems.

In addressing these issues, Samborsky, et al., (2009), applied the finite element analysis technique, where they explores the interactions between the thick adhesive joint geometry of turbine blade joints, as well as their local stress concentrations and pore hole locations. Campilho, et al., (2011), applied a finite element method to simulate the strength of adhesive joint, such that the strength of the bonded structure was predicted using strength of materials and fracture mechanics-based criteria. Tan & Saha, (2007), investigates the deformation characteristics of GFRP-bonded RC beams under cyclic loading, the beam stiffness was found to reduce more significantly for larger load ranges and lower minimum load levels. The integration and understanding of these characteristics in these research studies, all work together with the major contributions on the design rules of structural adhesive bonded joints (Van, et al., 1998). Papini, et al., (1994), investigate the influence of varying geometric parameters like the adherend lengths and thicknesses on the strength of adhesively bonded joints using a single lap shear, cracked lap shear, and double strap joints.

Suárez, et al., (2003), discuss the selection and analysis of adhesively bonded joints, while Arenas et al., (2012), propose the analytical hierarchy process (AHP) method for selecting the best adhesive material from a list of five materials. The method used in this study however, is only suitable when the number of alternatives is discrete and based on the formation of a hierarchical problem structure that supports the interactions of conflicting criteria. In this present work, an alternative method is proposed. The new method which is based on the integration of a Fuzzy Normalized-Hamming distance and Ideal Alternative (FL2DIA) model is used for the holistic evaluation of the different families of adhesive materials used in the formation of joints in mechanical systems. The adhesive materials are evaluated with respect to some selected fracture mechanics-based criteria using expert-based opinion (see Table 1). The advantage of using this method is that, it is able to holistically account for all the different adhesive materials including those that were not mention in the previous studies as well as to access them with respect to the fracture mechanics-based criteria. Also, it requires less mathematic skills, repetitive adjustment of data and inconsistency in the final result.

The rest of the paper is organized as follows; in section 2, the method for the evaluation of the adhesive materials with respect to the fracture mechanics-based criteria is presented. The application of the method is presented in Section 3, while so closing remarks are presented in Section 4.

**Table 1:** List of adhesive materials and the selected fracture mechanics-based criteria

Adhesive Materials	Code	Adhesive Materials	Code
Rubber adhesive	A <sub>1</sub>	PVA adhesive and related emulsion systems	A <sub>11</sub>
Polyurethane	A <sub>2</sub>	Plastisols and elastosols adhesive	A <sub>12</sub>
Acrylic	A <sub>3</sub>	Cyanoacrylate	A <sub>13</sub>
Anaerobic	A <sub>4</sub>	Silicone	A <sub>14</sub>
Solvent-based adhesive	A <sub>5</sub>		
Hot-melt adhesive	A <sub>6</sub>	<b>Fracture mechanics-based criteria</b>	<b>Code</b>
Amino or urea-based adhesive	A <sub>7</sub>	Fracture toughness	C <sub>1</sub>
Phenolics and resorcinolic adhesive	A <sub>8</sub>	Crack-resistance	C <sub>2</sub>
Epoxy	A <sub>9</sub>	Yield strength	C <sub>3</sub>
Polyimides and bismaleimides adhesive	A <sub>10</sub>	Fatigue threshold	C <sub>4</sub>

## 2. Methodology

### 2.1. Fuzzy Normalized-Hamming distance and Ideal Alternative (FL<sub>2</sub>DIA) model

The Fuzzy Normalized-Hamming distance (FL<sub>2</sub>), which is one of the distances methods applied for multi-criteria decision-making problems, is used to estimate the ideal distance between alternatives. Ideal alternatives are said to be virtual alternatives in which their criteria values are expressed as close as possible to ideal values. In this paper, the FL<sub>2</sub> distance is integrated with the Ideal Alternative method originally proposed by Tran & Boukhatem (2008). The FL<sub>2</sub>DIA method assumes that the determination of an ideal alternative is based on the optimum value of the criterion in which that alternative should achieve.

The FL<sub>2</sub>DIA method belongs to the category of Multiple Attribute Decision-Making (MADM) method originally developed by Lahby et al. (2012), and its implementation is similar to the M-TOPSIS

model developed by Ren et al., (2007) and model developed by Ren et al., (2007) and its extensions presented in (Aikhuele & Turan, 2017); Aikhuele & Turan, 2016). Only that it uses the Mahalanobis distance method. The application of the FL<sub>2</sub>DIA method is based on its ability to evaluate the distance between ideal alternatives. It takes into consideration the correlation with different alternatives and it can be used in choosing or selecting optimal data for other applications. The steps for the implementation of the FL<sub>2</sub>DIA method are presented below;

**Step 1.** Engage a group of Experts/Decision Makers (DMs). With their expert opinion, construct a fuzzy decision matrix  $D_{n \times m}(x_{ij})$  of the alternatives ( $A_i$ ) with respect to the fracture-based criteria ( $C_i$ ) presented in the introduction section, using linguistic variables and the fuzzy number (see Table 2)

$$x_{ij} = (a_{ij}, b_{ij}, c_{ij}), \quad i = 1, 2, \dots, m; \quad j = 1, \dots, n$$

$$D_{n \times m}(x_{ij}) = \begin{bmatrix} (a_{11}, b_{11}, c_{11}) & (a_{12}, b_{12}, c_{12}) & \dots & (a_{1n}, b_{1n}, c_{1n}) \\ (a_{21}, b_{21}, c_{21}) & (a_{22}, b_{22}, c_{22}) & \dots & (a_{2n}, b_{2n}, c_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (a_{m1}, b_{m1}, c_{m1}) & (a_{m2}, b_{m2}, c_{m2}) & \dots & (a_{mn}, b_{mn}, c_{mn}) \end{bmatrix} \quad (1)$$

**Table 2:** Fuzzy numbers for approximating the linguistic variable

Linguistic terms	Fuzzy Numbers
Very low (SL)	(0.1, 0.25, 0.3)
Low (LW)	(0.2, 0.3, 0.55)
Good (GD)	(0.3, 0.45, 0.6)
High (HH)	(0.5, 0.6, 0.7)
Excellent (EX)	(0.6, 0.75, 0.9)

**Step 2:** Using a weighted normalization method, normalize the fuzzy decision matrix by multiplying each element in the column in the fuzzy decision matrix by a pre-determined weight of the fracture-based criteria ( $\tilde{w}_j$ ).

$$\tilde{V} = [x_{ij} \times \tilde{w}_j]_{m \times n}, \quad (2)$$

for  $i = 1, \dots, n$  and  $j = 1, 2, \dots, m$

**Step 3:** Determine the positive and negative ideal solution (PIS) and (NIS) respectively for the FL<sub>2</sub>DIA model.

$$A^+ = \{\tilde{v}_1^+, \tilde{v}_j^+, \dots, \tilde{v}_m^+\} \quad (3)$$

where  $\tilde{v}_j^+ = (1, 1, 1), \quad j = 1, \dots, n$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_j^-, \dots, \tilde{v}_m^-\} \quad (4)$$

where  $\tilde{v}_j^- = (0, 0, 0), \quad j = 1, \dots, n$

**Step 4:** Compute the separation measures ( $d^+_i(A^+, A_i)$  and ( $d^-_i(A^-, A_i)$  for each alternative from the positive ideal and negative ideal solutions using the equations below which represents the Fuzzy Normalized-Hamming distance FL<sub>2</sub>.

$$d(\tilde{A}, \tilde{B})_{FL2i^+} = \sqrt{\sum_{i=0}^n \frac{1}{6} [(a_{ij} - \tilde{v}_j^+)^2 + 4(b_{ij} - \tilde{v}_j^+)^2 + (c_{ij} - \tilde{v}_j^+)^2]} \quad (5)$$

$$d(\tilde{A}, \tilde{B})_{FL2i^-} = \sqrt{\sum_{i=0}^n \frac{1}{6} [(a_{ij} - \tilde{v}_j^-)^2 + 4(b_{ij} - \tilde{v}_j^-)^2 + (c_{ij} - \tilde{v}_j^-)^2]} \quad (6)$$

*Remark:* At this stage, the result of the Fuzzy Normalized-Hamming distance (FL<sub>2</sub>) is integrated with the Ideal

Alternative method (DIA) originally proposed by Tran & Boukhatem (2008).

**Step 5:** Determine the “positive ideal alternative” (PIA) where  $d(\tilde{A}, \tilde{B})_{L2_{i+}}$  is the minimum value and  $d(\tilde{A}, \tilde{B})_{L2_{i-}}$  the maximum. The PIA is given as; (Tran & Boukhatem 2008).

$$PIA = \min d(\tilde{A}, \tilde{B})_{L2_{i+}}, \max d(\tilde{A}, \tilde{B})_{L2_{i-}} \quad (7)$$

**Step 6:** Using the PIA values in Step 5, determine the distance of an alternatives

$$PIA_{D_i} = \sqrt{\left[ \left( d(\tilde{A}, \tilde{B})_{L2_{i+}} - \min d(\tilde{A}, \tilde{B})_{L2_{i+}} \right)^2 + \left( d(\tilde{A}, \tilde{B})_{L2_{i-}} - \max d(\tilde{A}, \tilde{B})_{L2_{i-}} \right)^2 \right]} \quad (8)$$

**Step 8:** Finally, the  $PIA_{D_i}$  is ranked in the descending order

determined prior to the evaluation, the criteria were all found to be equal (i.e. equal to 1). This is due to the sensitivity of the using criteria as it relates to the different adhesive materials. In another word, no one criterion is found to be more important than the other when evaluating these adhesive materials.

### 3. Numerical application of the FL2DIA model for evaluating adhesive materials

The objective of using FL2DIA model in this study, is to holistically evaluate the different families of adhesive materials used in joining wind turbine blades system with respects to some selected fracture mechanics-based criteria and to identify potential adhesive material for the formation of joints in commercial aircraft.

The experts employed in the evaluation of the criteria and the adhesive materials in this study, were all drawn from the academia. Prior to the evaluations, they were all brief on the purpose of the study and the need to critically examine the questionnaire before answering them. The expert’s ratings ( $E_i$ ) of the different adhesive materials with respect to the criteria are presented in Table 3 and 4, were the information consists of linguistic variables, and the converted fuzzy numbers which represent the comprehensive decision matrix of the FL2DIA model.

In using the implementation steps for the FL<sub>2</sub>DIA model stated in Section 2, the different adhesive materials with respects to the fracture mechanics-based criteria are evaluated. It is important to note here that the weights for the criteria were pre-

**Table 3:** Ratings of the of the Adhesive materials with respect to the criteria

C <sub>i</sub>	E <sub>1</sub>	E <sub>2</sub>	E <sub>3</sub>	E <sub>1</sub>	E <sub>2</sub>	E <sub>3</sub>	E <sub>1</sub>	E <sub>2</sub>	E <sub>3</sub>	E <sub>1</sub>	E <sub>2</sub>	E <sub>3</sub>
	C1			C2			C3			C4		
A <sub>1</sub>	LW	GD	SL	HH	LW	HH	SL	HH	GD	GD	LW	SL
A <sub>2</sub>	HH	HH	SL	EX	GD	EX	LW	EX	HH	SL	GD	LW
A <sub>3</sub>	EX	EX	LW	SL	HH	HH	GD	HH	EX	LW	HH	GD
A <sub>4</sub>	HH	HH	GD	LW	GD	GD	LW	LW	SL	GD	LW	SL
A <sub>5</sub>	HH	GD	LW	GD	HH	GD	HH	GD	LW	LW	GD	LW
A <sub>6</sub>	SL	GD	HH	H	EX	HH	EX	LW	SL	GD	HH	GD
A <sub>7</sub>	LW	HH	SL	EX	HH	HH	LW	GD	LW	HH	GD	HH
A <sub>8</sub>	HH	EX	LW	SL	EX	EX	GD	HH	GD	GD	HH	LW
A <sub>9</sub>	SL	HH	HH	SL	HH	HH	SL	GD	SL	GD	SL	GD
A <sub>10</sub>	LW	SL	EX	LW	EX	EX	LW	LW	LW	HH	LW	HH
A <sub>11</sub>	GD	LW	HH	SL	HH	HH	GD	GD	GD	EX	GD	HH
A <sub>12</sub>	SL	HH	GD	HH	HH	GD	SL	HH	HH	LW	EX	GD
A <sub>13</sub>	LW	SL	EX	SL	SL	SL	SL	SL	HH	GD	HH	HH
A <sub>14</sub>	HH	LW	HH	GD	LW	GD	GD	LW	HH	LW	EX	GD

**Table 4:** Decision matrix for the FL<sub>2</sub>DIA method

	C1	C2	C3	C4
A <sub>1</sub>	(0.20, 0.33, 0.48)	(0.40, 0.50, 0.65)	(0.30, 0.43, 0.53)	(0.20, 0.33, 0.48)
A <sub>2</sub>	(0.37, 0.48, 0.57)	(0.47, 0.65, 0.80)	(0.43, 0.55, 0.72)	(0.20, 0.33, 0.48)
A <sub>3</sub>	(0.47, 0.60, 0.78)	(0.37, 0.48, 0.57)	(0.47, 0.60, 0.73)	(0.33, 0.45, 0.62)
A <sub>4</sub>	(0.43, 0.55, 0.67)	(0.27, 0.40, 0.58)	(0.17, 0.28, 0.47)	(0.20, 0.33, 0.48)
A <sub>5</sub>	(0.33, 0.45, 0.62)	(0.37, 0.50, 0.63)	(0.33, 0.45, 0.62)	(0.23, 0.35, 0.57)
A <sub>6</sub>	(0.30, 0.43, 0.53)	(0.53, 0.65, 0.77)	(0.30, 0.43, 0.58)	(0.37, 0.50, 0.63)
A <sub>7</sub>	(0.27, 0.38, 0.52)	(0.53, 0.65, 0.77)	(0.23, 0.35, 0.57)	(0.43, 0.55, 0.67)
A <sub>8</sub>	(0.43, 0.55, 0.72)	(0.43, 0.58, 0.70)	(0.37, 0.50, 0.63)	(0.33, 0.45, 0.62)
A <sub>9</sub>	(0.37, 0.48, 0.57)	(0.37, 0.48, 0.57)	(0.17, 0.32, 0.40)	(0.23, 0.38, 0.50)
A <sub>10</sub>	(0.30, 0.43, 0.58)	(0.47, 0.60, 0.78)	(0.20, 0.30, 0.55)	(0.40, 0.50, 0.65)
A <sub>11</sub>	(0.33, 0.45, 0.62)	(0.37, 0.48, 0.57)	(0.30, 0.45, 0.60)	(0.47, 0.60, 0.73)
A <sub>12</sub>	(0.30, 0.43, 0.53)	(0.43, 0.55, 0.67)	(0.37, 0.48, 0.57)	(0.37, 0.50, 0.68)
A <sub>13</sub>	(0.30, 0.43, 0.58)	(0.10, 0.25, 0.30)	(0.23, 0.37, 0.43)	(0.43, 0.55, 0.67)
A <sub>14</sub>	(0.40, 0.50, 0.65)	(0.27, 0.40, 0.58)	(0.33, 0.45, 0.62)	(0.37, 0.50, 0.68)

In Step 3-8 of the FL<sub>2</sub>DIA model algorithm, the decision matrix presented in Table 4 is normalized to form the weighted normalized decision matrix. Thereafter, the Fuzzy Normalized-Hamming distance (FL<sub>2</sub>) to the positive and negative alternatives is

computed. From the Fuzzy Normalized-Hamming distance the PIA is determined and finally, the PIA result is ranked in the descending order as shown in Table 5.

**Table 5:** The FL<sub>2</sub>DIA result

	$d(\tilde{A}, \tilde{B})_{L2i+}$	$d(\tilde{A}, \tilde{B})_{L2i-}$	$PIA_{D_i}$	Ranking
A <sub>1</sub>	1.218	0.827	0.376	12
A <sub>2</sub>	1.032	1.045	0.093	3
A <sub>3</sub>	0.951	1.092	0.000	1
A <sub>4</sub>	1.234	0.833	0.384	13
A <sub>5</sub>	1.126	0.914	0.249	10
A <sub>6</sub>	1.023	1.031	0.094	4
A <sub>7</sub>	1.063	1.016	0.135	7
A <sub>8</sub>	0.972	1.062	0.036	2
A <sub>9</sub>	1.198	0.841	0.351	11
A <sub>10</sub>	1.097	0.976	0.186	9
A <sub>11</sub>	1.026	1.012	0.110	5
A <sub>12</sub>	1.034	0.995	0.127	6
A <sub>13</sub>	1.243	0.831	0.391	14
A <sub>14</sub>	1.075	0.960	0.180	8

From Table 5, it is not hard to see that the adhesive material with the highest potential to be used for joining the wind turbine blade with respect to the fracture mechanics-based criteria is the Acrylic adhesive material which is represented with the code **A<sub>3</sub>**. The study can conclude therefore that, the procedure described for the evaluation of the adhesive material has led to the selection of the best structural adhesive for bonding the

FRP wind turbine blade. This has also confirmed in the following literatures (Arenas et al., 2012; Briggs & Jialanella, 2010) where Acrylic adhesive material is confirmed as one of the strongest adhesives for bonding metal, glass and plastic. It requires a minimum surface preparation before its applications in joints and has been found to be one of the excellent temperature resistance adhesive materials. Hence, it is



identified as a potential adhesive material for the formation of joints in a commercial aircraft with respect to some the selected fracture mechanics-based criteria. The study has revealed the suitability of using the proposed method for ranking alternatives in the presents of conflicting criteria.

Finally, to prove the rationality and feasibility of the FL<sub>2</sub>DIA method, the result presented in Table 5 is compared with similar existing method (traditional fuzzy TOPSIS model) under the same condition. The comparison result which focuses on the ranking of the adhesive material shows total agreement with the proposed method. The result is shown in Table 6.

**Table 6:** Comparison results for the FL<sub>2</sub>DIA and fuzzy TOPSIS

Alternatives	$PIA_{D_i}$	Ranking	$CC_i$	Ranking
A <sub>1</sub>	0.376	12	0.404	12
A <sub>2</sub>	0.093	3	0.503	3
A <sub>3</sub>	0.000	1	0.534	1
A <sub>4</sub>	0.384	13	0.403	13
A <sub>5</sub>	0.249	10	0.448	10
A <sub>6</sub>	0.094	4	0.502	4
A <sub>7</sub>	0.135	7	0.489	7
A <sub>8</sub>	0.036	2	0.522	2
A <sub>9</sub>	0.351	11	0.413	11
A <sub>10</sub>	0.186	9	0.471	9
A <sub>11</sub>	0.110	5	0.496	5
A <sub>12</sub>	0.127	6	0.490	6
A <sub>13</sub>	0.391	14	0.401	14
A <sub>14</sub>	0.180	8	0.472	8

#### 4. Conclusion

In this paper, a new method which is based on the integration of a Fuzzy Normalized-Hamming distance and Ideal Alternative (FL<sub>2</sub>DIA) method is proposed for the holistic evaluation of the different families of adhesive materials used in the formation of joints in mechanical systems including wind turbine blades. The adhesive materials which are evaluated with respect to the fracture mechanics-based criteria (fracture toughness  $C_1$ , crack-resistance  $C_2$ , yield strength  $C_3$ , and fatigue threshold  $C_4$ ) used expert-based opinion to select the best alternative.

From the result which shows that Acrylic adhesive material ( $A_3$ ) has the highest potential to be used for joining the wind turbine blade based on the fracture mechanics-based criteria. We can conclude that the procedure described for the evaluation of the adhesive material has led to the selection of the best structural adhesive to bond the FRP wind turbine blade. Also, it has revealed the suitability, rationality, and feasibility of using the proposed method for ranking the different adhesives materials. Furthermore, the results have been compared with a similar existing model -traditional fuzzy TOPSIS model- under the same condition. The comparison result which focuses on the ranking of the adhesive material shows total agreement. In future research, a method for the calculation of the criteria weights will be integrated into the method; this is to account for criteria that may have different sensitivity.

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