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FROM MECHANICAL TESTING TO DECISION MAKING: SELECTING A STRUCTURAL ADHESIVE USING THE WEIGHTED SUM METHOD

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ABSTRACT

The selection of structural adhesives in engineering applications demands a robust, transparent, and replicable methodology, especially when performance and reliability are critical. This study introduces a practical, scalable approach based on the Weighted Sum Method (WSM), a form of Multi-Criteria Decision Analysis (MCDA), to assist in the objective selection of adhesives. The novelty of this research lies in demonstrating that WSM can serve as an industrially applicable decision-making tool that translates mechanical testing data into clear, replicable selection criteria. Using experimental data from modified Arcan tests, the method provides a structured framework that can be extended to other types of tests and applications. This facilitates transparent, criterion-driven adhesive selection aligned with real-world constraints, offering engineers a powerful tool that supports consistent, informed, and reproducible decisions.

KEYWORDS: structural adhesives, mechanical test, decision criteria, WSM method

1. Introduction

In modern engineering applications, bonded assemblies have emerged as a crucial structural solution, offering significant advantages over traditional mechanical assembly. These advantages include improved stress distribution, reduced weight, and enhanced fatigue resistance. Structural adhesives are at the core of this advancement, enabling the reliable joining of dissimilar materials under complex loading conditions. Consequently, understanding and predicting the mechanical behavior of bonded joints is essential for ensuring the durability and performance of assembled structures in critical fields such as aerospace, automotive, and marine engineering [1].

The mechanical performance of an adhesive can be characterized at two distinct levels: as a bulk material and as part of a functional bonded joint. Bulk adhesive specimens provide an effective means for intrinsic material characterization, isolating the adhesive from substrate interactions and interface effects [2]. Standard uniaxial tensile (EN ISO 527-2), compression (ASTM D695), and shear tests [3-4] are commonly employed to determine fundamental properties such as Young's modulus, yield stress, and ultimate strength. However, these tests often fail to capture the complex stress states and degradation phenomena that occur within a bonded joint.

In practical assemblies, adhesives are rarely subjected to pure stress states; instead, they often face multi-axial loading and environmental influences, such as humidity and temperature variations. To address these complexities, test configurations that simulate real-world conditions are indispensable. Among the various test setups, the modified Arcan fixture has gained prominence due to its capacity to apply a wide range of loading angles—ranging from pure shear to pure tension or compression—by simply altering the orientation of the device relative to the testing machine [2, 5]. This versatility makes the Arcan method particularly suitable for robust mechanical characterization, especially when studying the coupling of mechanical loading and environmental effects.

The modified Arcan device offers several improvements over standard fixtures. Firstly, it facilitates uniform stress distribution within the adhesive layer, minimizing the effect of edge-induced stress concentrations commonly encountered in lap-shear tests [6-7]. Secondly, its ability to simulate multi-axial stress states enables a more comprehensive understanding of adhesive performance under realistic service conditions [8-9]. Finally, it allows precise parameter calibration for advanced constitutive models if needed [10].

Despite these experimental advancements, the adhesive selection process in industry remains challenging due to the multitude of performance criteria, from mechanical strength to environmental resistance and ease of application. While empirical testing provides valuable data, the final adhesive choice must consider multiple, sometimes conflicting, criteria that align with project-specific requirements. As such, the integration of a structured decision-making framework becomes necessary.

To support objective adhesive selection, decision-making tools such as Multi-Criteria Decision Analysis (MCDA) methods have gained traction in engineering applications. MCDA provides a structured approach to evaluating various alternatives based on multiple attributes, making it particularly suitable for industrial contexts where decisions must be made quickly, consistently, and transparently [11]. Among the spectrum of MCDA tools, the Weighted Sum Method (WSM) stands out for its simplicity, low computational effort, and ease of implementation [12]. In WSM, the final decision score is calculated as a linear combination of weighted performance scores across selected criteria, allowing for straightforward comparisons between competing adhesives.

Given the need for efficiency and clarity in the adhesive selection process, WSM is adopted in this study as the decision-support framework. Its intuitive formulation allows engineers and decision-makers to balance mechanical performance metrics obtained from experimental testing—especially those derived from modified Arcan tests—with practical considerations. This approach ensures that the selected adhesive not only meets mechanical and environmental demands but also integrates seamlessly into broader project goals.

In summary, this article bridges the gap between mechanical characterization and engineering decision-making. Through the use of advanced experimental methods like the modified Arcan test and a structured MCDA tool such as WSM, we propose a comprehensive framework for the robust selection of structural adhesives. This framework is designed to enhance reliability, reduce trial-and-error in product development, and facilitate the systematic integration of experimental insights into engineering practice.

2. Material and experimental methods

2.1. General information on the adhesives

The objective of this project is to identify and characterize a structural bonding solution suitable for applications in marine environments. Due to their favourable aging behavior under humid conditions, two types of two-component epoxy adhesives were proposed.

For confidentiality reasons, the commercial names of these adhesives cannot be disclosed. Therefore, the two adhesives will be referred to as Adhesive A and Adhesive B throughout this document. These adhesives were proposed by the industrial partner, and the purpose of the following sections is to evaluate them in order to identify the most suitable solution for the targeted application.

Adhesive A and Adhesive B are two-component epoxy paste adhesives already used in various industrial applications. According to the manufacturer, both adhesives demonstrate high shear strength, long-term durability, and resistance to moisture-induced aging—essential properties for marine environments. Both adhesives are supplied with 2 components (resin and hardener), and the mixing of each adhesive must strictly respect the ratios specified by the manufacturer and indicated in Tables 1 and 2.

According to Tables 1 and 2, for each of the two adhesives, the epoxy resin and its corresponding hardener must be mixed at room temperature in the ratio specified by the manufacturer. These components are mixed in 50 mL or 100 mL polypropylene containers, which limit adhesion. A laboratory balance, the Precise™ XT22A, ensures the accuracy of the mixing ratio.

Table 1. *Technical specifications for adhesive A*

Property	*Resin*	*Hardener*	*Mixture*
Color (visual)	Yellow	Blue	Dark green
Density	1.2	1.0	~1.1
Viscosity at 25 °C (Pa.s)	100-300	0.6-1.4	35-45
Pot life (100 g at 25 °C)	-	-	120-200 min
Shear strength at 23 °C	-	-	>30 MPa
Mixing ratio (by weight)	100	40	-
Mixing ratio (by volume)	100	50	-

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Table 2. *Technical specifications for adhesive B*

Property	*Resin*	*Hardener*	*Mixture*
Color (visual)	Gray	Beige	Gray
Density	1.4	0.9	~1.2
Viscosity at 25 °C (Pa.s)	380-720	Thixotropic	Thixotropic
Pot life (100 g at 25 °C)	-	-	80-90 min
Shear strength at 23 °C	-	-	>17 MPa
Mixing ratio (by weight)	100	60	-
Mixing ratio (by volume)	100	100	-

Previous experiments [10, 13] have shown that optimal homogeneity is achieved using a Speedmixer™ DAC 150.1 FVZ. This specialized device mixes for 0 to 5 minutes at speeds ranging from 300 to 3500 rpm. For both adhesives, a speed of 2500 rpm was used for 4 minutes. These parameters ensure the desired homogeneity without overheating the mixture.

Finally, the mixture can be used within the pot life specified by the manufacturer (Tables 1 and 2) to bond surfaces that have been pre-prepared (e.g. by cleaning and mechanical polishing). The assembled joints are then subjected to the recommended polymerization cycles.

For epoxy adhesives, the choice of the polymerization cycle significantly affects the resulting mechanical properties. According to the manufacturer, shear strength may vary depending on the temperature and duration of the curing cycle.

The polymerization cycles used in this study were defined by the industrial partner based on the specifics of the intended application, and are listed in Table 3. These conditions are strictly followed throughout the fabrication of all bonded assemblies.

The experimental setup used to carry out these polymerization cycles is a Memmert UF 110 climate chamber, which provides a temperature range from 20 °C to 310 °C.

Table 3. *Polymerization Cycles*

Adhesive	*Temperature*	*Duration*
A	50 °C	12 hours
B	23 °C	7 days

2.2. Sample Preparation

In order to study the mechanical behavior of adhesives, modified Arcan tests were performed. Several previous studies [6, 14-16] have highlighted the relevance of these tests for the mechanical characterization of bonded joints. This test campaign provides a basis for comparing the mechanical performance of the two proposed adhesives, independent of the substrates used. In this section, we present the experimental protocol and the results of these tests.

The geometry of the samples used is shown in Figure 1. Various researchers have demonstrated that this geometry yields good repeatability under different loading types and conditions [10, 13-14, 17-18].

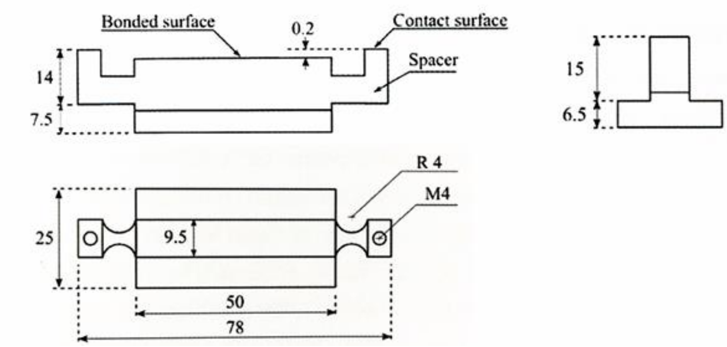

Fig. 1. *Main dimensions of the geometry (not to scale)* [19]

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A key feature of the Arcan specimen is the presence of "beaks" (Fig. 2) that minimize edge effects during the test. These features reduce stress concentrations at the adhesive joint edges, allowing characterization without premature crack initiation. Additionally, the loading condition promotes cohesive failure (within the adhesive) rather than adhesive failure (at the interface with the substrates).

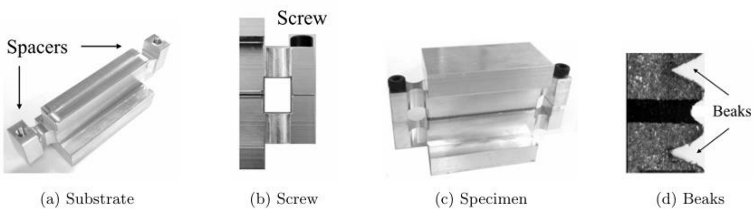

Fig. 2. *Modified Arcan specimen* [10]

An Arcan specimen is assembled by bonding two substrates as shown in Figure 2. The bonding procedure begins with surface preparation: fine polishing using abrasive paper (grade #180) to ensure optimum adhesion (Fig. 3.a). The adhesive is then applied to the two substrates (Fig. 3.b), which are aligned and held in place by screws through spacers (Fig. 3.c). The spacers align the substrates and maintain this position during bonding. Their thickness also controls the thickness of the adhesive layer (typically 0.4 mm). For reasons of reproducibility, screws are tightened to 1.5 N-m using a torque screwdriver. After assembly, the polymerization cycle specific to each adhesive (Table 3) is applied.

Finally, spacers are removed and the specimen is ready for testing. A speckle pattern (Fig. 3.d) may be applied for Digital Image Correlation (DIC), which is explained further in this section.

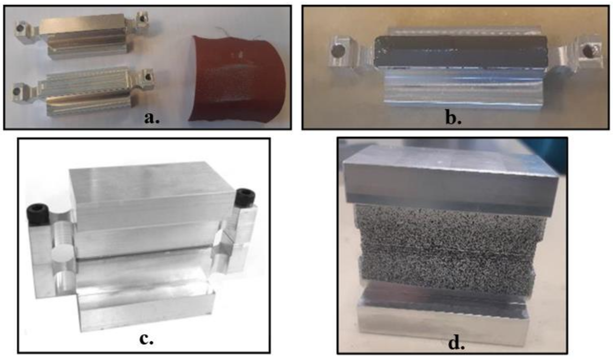

Fig. 3. *Sample preparation: a - surface polishing; b - adhesive application; c - assembled sample; d - sample ready for testing*

2.3. Substrates

The substrates are made of aluminium alloy AW2017, chosen for its ease of machining and resistance to harsh environmental conditions. Some of its mechanical properties are shown in Table 5.

Table 5. *Mechanical Properties of AW2017 Aluminium Alloy*

Properties	*Value*	*Unit*
Density	8	*g.cm^{-3}*
Thermal conductivity	130-200	*W.mK^{-1}*
Young's modulus	75	*GPa*
Shear modulus	27.2	*GPa*
Tensile strength	250-370	*MPA*

2.4. Experimental Setup

The test setup is shown in Figure 4 and includes:

• The INSTRON 1342 tensile testing machine (Fig. 4.a);

• The modified Arcan fixture (Figure 7);

• The GOM 5M Digital Image Correlation (DIC) system (Figures 4.b, 4.c)

The INSTRON machine uses hydraulic actuation. Main specifications are shown in Table 6.

Table 6. *INSTRON 1342 specifications*

Specifications	*Value*	*Unit*
Max force	+/-100	*kN*
Max speed	10	*mm/s*

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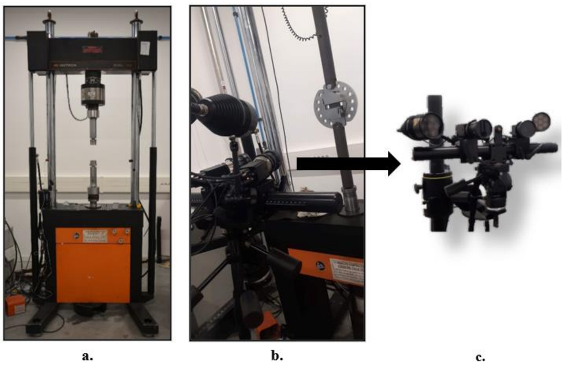

***Fig. 4.** Experimental set-up for Arcan tests: a - INSTRON 1342; b - Arcan set-up during test; c - GOM 5M*

The modified Arcan fixture allows combined loading conditions (tension, shear, or mixed tension-shear). By rotating the fixture by an angle θ relative to the machine's axis, the loading type can be easily changed. Figure 5. shows the three applied loading types.

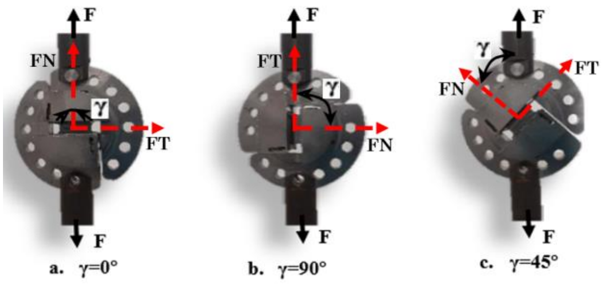

***Fig. 5.** Different loads applied with the Arcan device: a - tensile; b - shear; c - tensile-shear*

Digital image stereo-correlation (DIC) is the preferred method of test analysis, particularly in the field of research, because of its ability to accurately follow sample displacements and deformations during testing. The special feature of DIC is access to the distribution of kinematic fields, such as displacements and even deformations, enabling out-of-plane displacements to be determined. Further details can be found in the literature [20].

The GOM 5M digital image stereo-correlation system, shown in Figure 4.c, consists of two cameras which record images during the test at a set frequency. The advantage of using DIC is that it can also detect motion in a third direction (out-of-plane), making it independent of the relative positron variation between sample and system.

DIC is used to determine the displacement fields and, by derivation, the deformation of the sample. The principle of this method is based on the tracking of a pattern identified in the reference image for all so-called deformed images. The set of recorded images forms a film, from which we extract a measurement. Random coding is achieved using two spray paints (white and black). First of all, a white background is created, onto which black spots with dimensions ranging from 100 µm to 1000 µm are applied (Fig. 6).

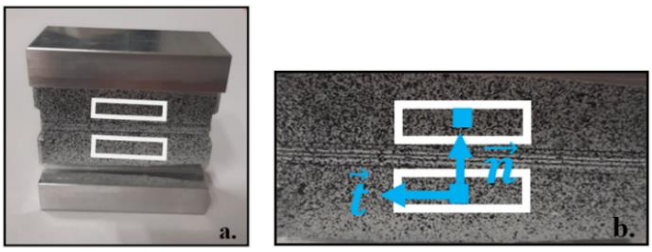

***Fig. 6.** A sample coded with a random pattern: a - area of interest; b - normal and tangential directional vectors*

Finally, the recorded test data (images and associated forces) with the digital image stereo-correlation system are analysed using ARAMIS v6.3.1 software. In the case of the Arcan sample, the area of interest to be analysed is chosen in the central part of the substrate, close to the adhesive joint (Fig. 6). More precisely, displacement fields are measured in the normal and tangential directions between these two zones of interest, as illustrated in Figure 6.b.

These experimental tools for modified Arcan device enable robust experimental characterization of the adhesive joint, leading to reliable results through judicious exploitation of these displacement or deformation fields.

3. Results

3.1. Experimental test results

Fig. 7 presents the results from the main Arcan tests performed. These are all monotonic tests conducted under force control, with a loading rate of 0.2 kN/s. Displacement fields measured via DIC allows us the reconstruction of force–displacement curves, where the displacement represents the relative movement between the two bonded substrates.

Here, the x-axis of the graphs in Figure 7 represents the relative displacement (normal or tangential) between two points on the substrates located 1.5 mm from the mid-plane of the adhesive joint (Fig. 6). The y-axis represents the corresponding force measured in the same direction by the load cell.

As discussed earlier, loading configurations include:

- Tension (Figure 7.a);
- Shear (Figure 7.b);
- Combined tension-shear at 45° (Figures 7.c and 7.d show normal and tangential force-displacement curves respectively).

These initial mechanical tests allow us comparison of the two adhesives — A and B. Three tests were conducted for each loading type, and good repeatability was observed for both adhesives.

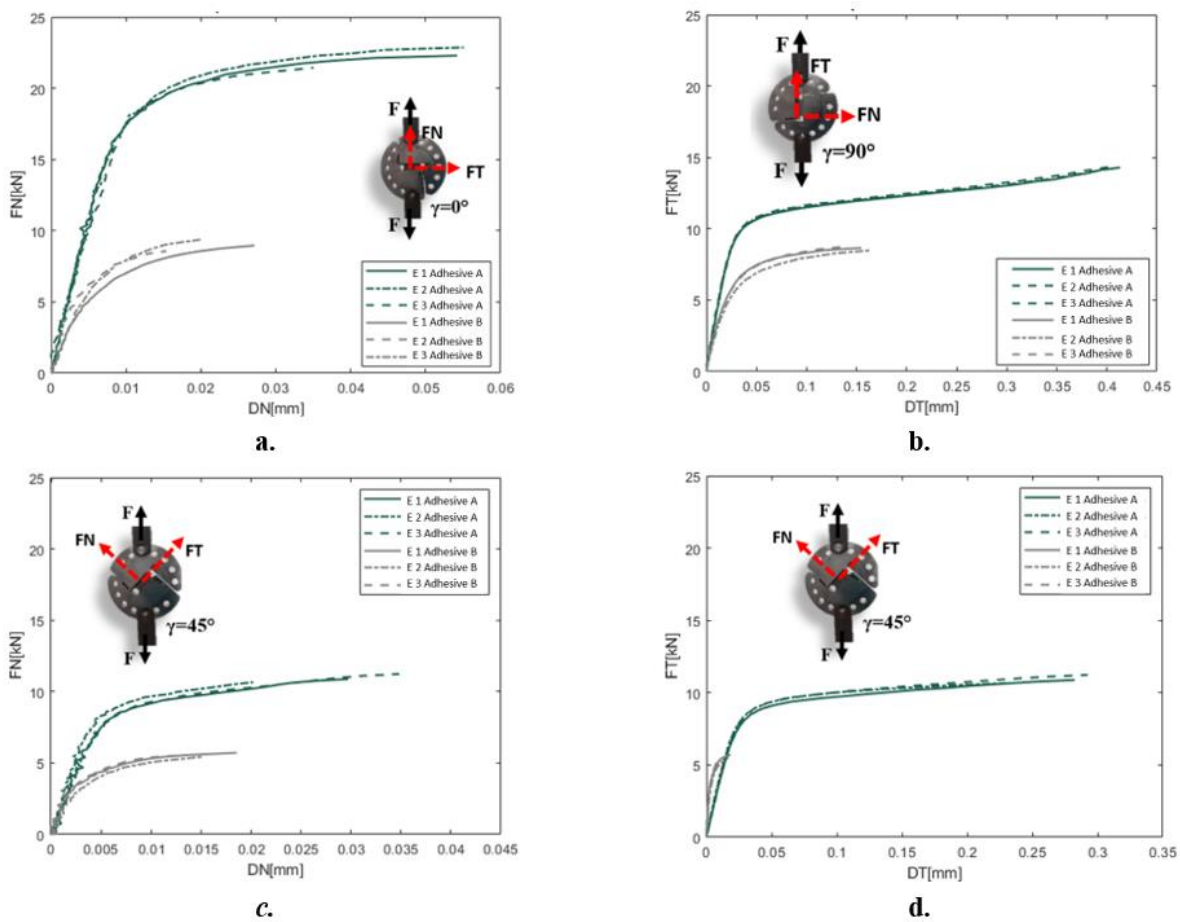

Fig. 7. *Adhesive behavior: a - tensile; b - shear; c - tension-shear (FN); d - tension-shear (FT)*

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Preliminary analysis of these curves reveals that the mechanical properties of adhesive A (e.g., apparent yield limit and ultimate force) are significantly higher than those of adhesive B, across all three loading types (tension, shear, and combined tension-shear).

Figure 8 summarizes the ultimate loads obtained for both adhesives under different loadings. In each case, the variation in maximum force between tests is less than 5% of the average value. This figure clearly highlights the performance gap between the two adhesives.

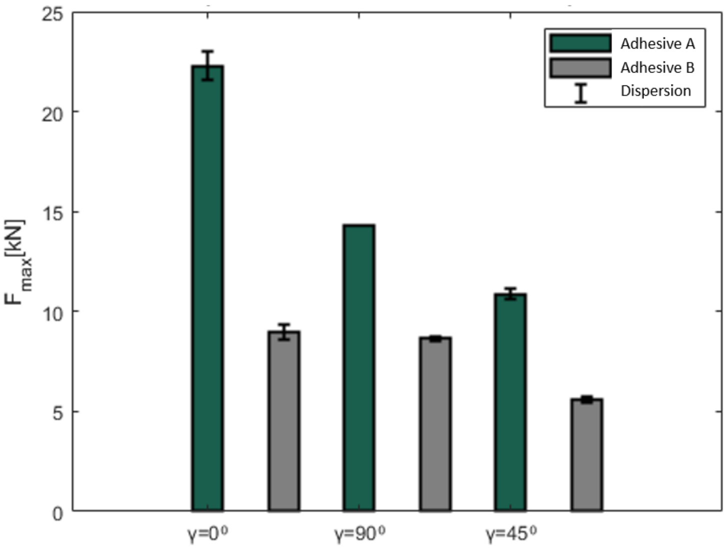

Fig. 8. *Dispersion in fracture behavior*

Figures 9 and 10 show the envelopes of the yield stresses and breaking loads, respectively, for the two adhesives. These curves are plotted in the tension-shear plane, and strains are estimated by dividing the force by the bonded area. However, due to the non-uniform stress distribution in the modified Arcan sample, the average normal and shear strain are corrected using the following equations [8]:

$$\sigma_{max\ \_el} = 1.12\sigma_{moy}, avec\ :\sigma_{moy} = \frac{FN}{S_c} \tag{1}$$

$$\tau_{max\ \_el} = 1.29\tau_{moy}, avec : \tau_{moy} = \frac{FT}{S_c} \tag{2}$$

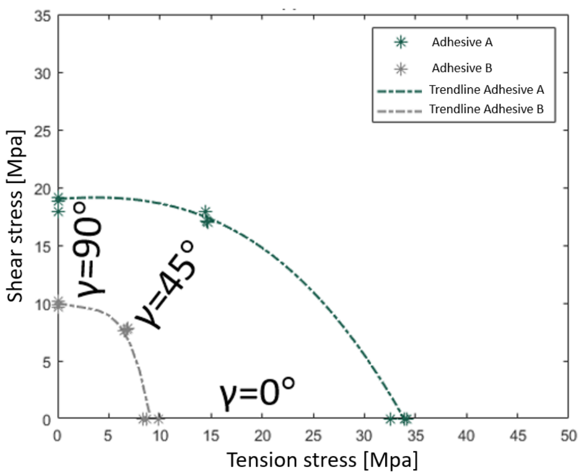

Fig. 9. *Elasticity envelopes*

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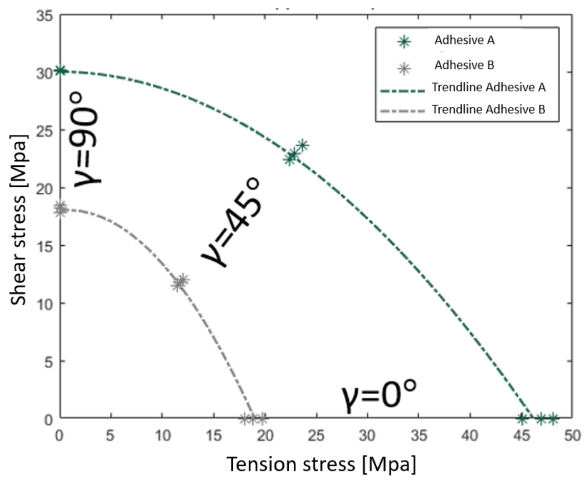

Fig. 10. Failure envelopes

These corrected stress estimates are consistent with values obtained through inverse identification techniques that model the test using finite element methods [8, 21].

Lastly, modified Arcan tests also provide insights through visual analysis of the fracture surfaces. Fracture patterns for samples bonded with adhesive B (Figures 11.A, 11.B, 11.C) suggest better adhesion to aluminium substrates compared to those bonded with adhesive A (Figures 11.D, 11.E, 11.F). In particular, joints bonded with adhesive B generally fail cohesively (within the adhesive), whereas joints bonded with adhesive A tend to show cohesive failure in tension (Figure 11.F) and mixed cohesive/adhesive failure under shear or combined load (Figures 11.D, 11.E).

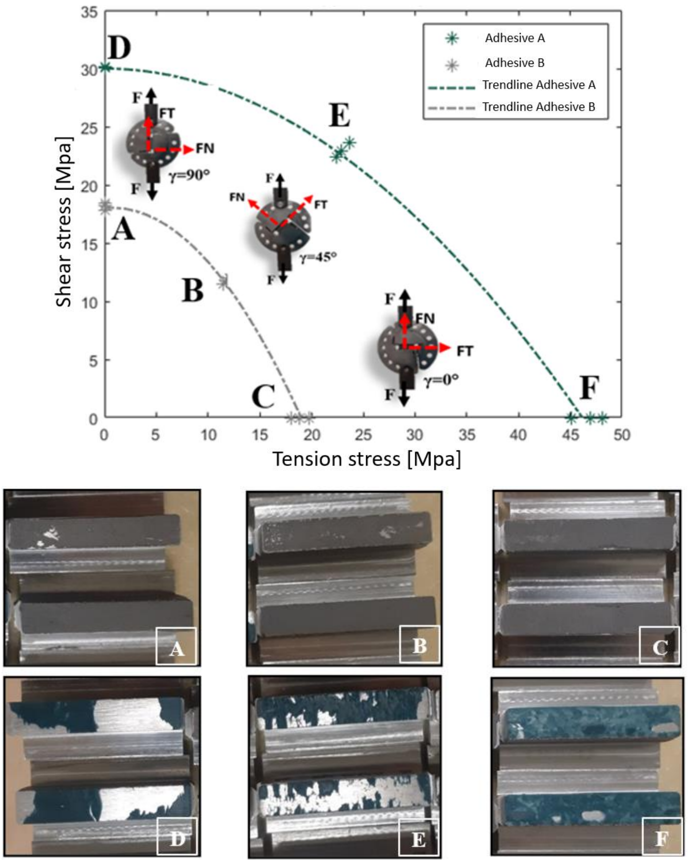

Fig. 11. Failure modes for each load type

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These experimental tests enabled us to identify the maximum force and the maximum strain at rupture under the assumption of complete plastic deformation. For the first part, we identified the elastic modulus. These parameters enabled us to compare the two adhesives in terms of mechanical behavior.

3.2. Selection of the Structural Adhesive

The work presented above, along with the results obtained, is intended to lead to an objective selection of the adhesive to be used in future analyses and applications. In order to choose the most appropriate adhesive, selection criteria must be defined in alignment with the project specifications.

The chosen criteria can be grouped and assessed using Multi-Criteria Decision Analysis (MCDA) methods. These methods are especially useful in industrial contexts due to their simplicity and ease of implementation. Numerous types of MCDA methods are documented in the literature. For example, Goh [22] provides a review of several widely used decision methods, evaluating their advantages and disadvantages — such as ease of implementation, required effort, and need for additional tools.

Figure 12 lists the main decision analysis methods cited in the literature, along with how frequently they appear in reported studies.

Given the need for a quick and simple analysis in this study, the Weighted Sum Method (WSM) was selected for choosing the optimal adhesive. WSM is an elementary MCDA method where the final value of a given solution is calculated as the sum of the weights of its evaluation against each criterion [22]. For more details, the mathematical principle of the process is described in [23].

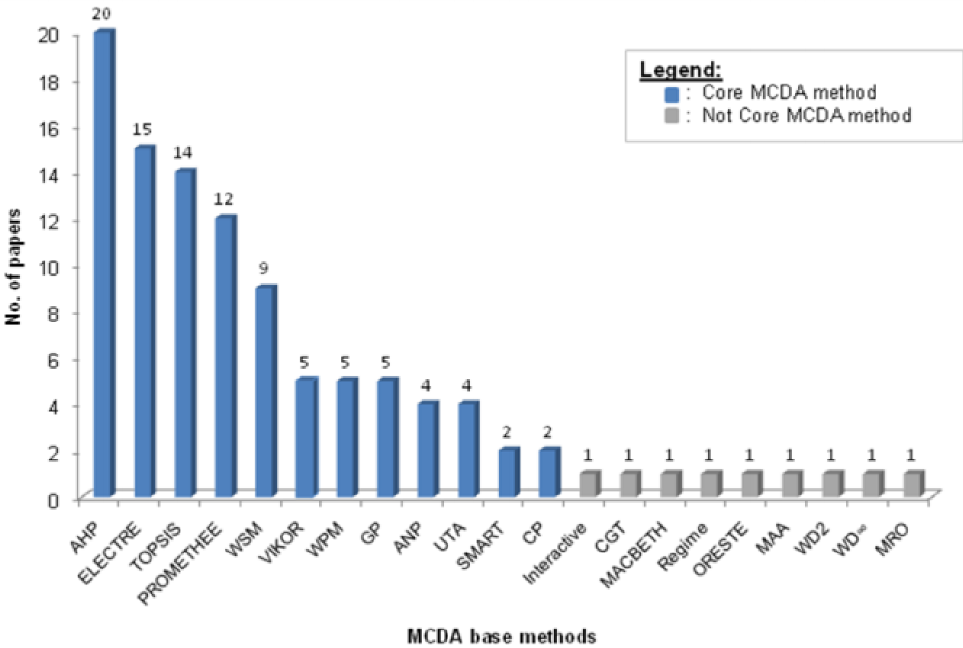

***Fig. 12.** The main decision analysis methods presented in the publications* [22]

The calculation procedure for adhesive selection by weighted sum is shown in Tables 7, 8 and 9. In particular, the method involves first establishing a weighting for each selected criterion (Table 7). On the basis of this weighting, the importance of the criterion given by scores from 0 (not important) to 3 (very important) was established. Secondly, the criteria are ranked by scores from 0 to 10 with the meaning explained in Table 8. According to this notation, a score closer to 0 means that the adhesive is not suitable under the given conditions, and a score closer to 10 indicates suitable properties. The final step in this method is the effective sum of these scores for each adhesive (Table 9). The scores given for each criterion are multiplied by their weight. The resultant product is added together to form a weighted sum representing the benchmark to be compared. The adhesive with the highest score is classified as optimal. Scores are given according to the results obtained from the experimental tests (modified Arcan).

Therefore, based on the scores obtained using this method, adhesive A is identified as the optimal adhesive for the considered application.

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Table 7. *Evaluation Weights*

Weight	*Meaning*
0	Not important
1	Slightly important
2	Important
3	Very important

Table 8. *Selection Criteria*

Criterion	*Min Score*	*Meaning*		*Max Score*	*Meaning*	
σ_{max} (strength)	0	0 MPa	No strength	10	40 MPa	Very high strength
$D_{\sigma_{max}}$ (Reproducibility)	0	>40% variation	Poor	10	<5% variation	Very good
N_f (Failure Mode)	0	Adhesive failure		10	Cohesive failure	

Table 9. *Weighted Sum Calculation*

Test Type	*Arcan*						*Total Weighted Score*
Criteria	σ_{max}		N_f		$D_{\sigma_{max}}$		
Weights	3		2		2		
Adhesive A	8	**24**	6	**12**	8	**16**	52
Adhesive B	4	**12**	9	**18**	7	**14**	44

4. Conclusions and perspectives

This study proposes a robust and scalable framework for selecting structural adhesives using a combination of experimental testing and the Weighted Sum Method for decision-making. The methodology was applied to two epoxy adhesives, evaluated through modified Arcan tests under tensile, shear, and mixed loading configurations. These tests provided a clear mechanical comparison of the adhesives, enabling their classification based on performance indicators such as strength, failure mode, and repeatability.

The novelty and strength of this approach lie in its flexibility and industrial relevance. By using WSM, the selection process becomes transparent and reproducible, enabling engineers to define weighted criteria that reflect the specific needs of an application. Although this study relied on a single type of mechanical test (modified Arcan), the methodology allows for the integration of additional tests—both on bulk adhesive properties (e.g., tensile, shear) and various joint configurations (e.g., TAST, butt-joint, etc.).

This strategy is particularly beneficial in industrial environments where adhesive performance must align with specific service conditions (e.g., temperature, humidity, dynamic loads). The method ensures that the test data used are representative of the application scenario and encourages execution under conditions close to real-world operation.

However, the proposed framework also has some limitations. We mention here the cost and duration of the experiments since performing the relevant mechanical tests, in particular on bonded joints, is resource intensive. Finally, subjectivity in scoring is also a limitation of the method. WSM relies on subjective scores assigned to each criterion, and if not carefully controlled, this could introduce bias into the decision.

In order to improve these aspects, two suggestions can be offered as a starting point for future work:

- Numerical simulation as a substitute or complement to experimental testing - If the mechanical behavior of adhesives and substrates is already known, simulations can reproduce the operating conditions and reduce the dependence on experimental testing.

- Minimize subjectivity - Ideally, scoring should be performed by multiple evaluators and the average score should be used in the WSM calculation. This collaborative assessment can reduce individual bias and improve the reliability of decisions.

In conclusion, this work demonstrates the utility of the WSM method in adhesive selection and encourages its broader use across various industrial contexts. The proposed method offers a systematic path from experimental mechanics to informed engineering decisions and can be adapted to a wide range of structural applications.

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