Effects of the single-lap joint on fatigue strength of metals with different surface coatings: a numerical simulation

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Abstract. Due to their low cost and ease of use, adhesives are frequently used in the industry. Selecting adherents and adhesives is essential when thinking about a construction that uses them. A fatigue study is therefore required to determine the best adherents and adhesives. In this situation, a prediction model must be incorporated into the process. In this study, Single-lap joint (SLJ) was chosen. Specimens with uncoated, primed, and cataphoresis-treated surfaces on DC01 steel sheet surfaces have been taken into account. A numerical solution was produced to obtain the fatigue life of the structures. Results indicate that the produced approach can provide an accurate estimate of fatigue resistance of different bonding methods including adhesive joints with various coating and adhesive thicknesses combined with adhesive techniques.

1 Introduction

Due to the intense rivalry conditions in today's global markets, where producers from every industry compete, it now refers to the difficulties of selling goods in any market over the world. If companies wish to meet these difficulties and stay one step ahead of their competitors, they must produce competitive, innovative products that consider global conditions. Manufacturers must overcome these challenges, to maintain or expand their share of the global market pie. Constant improvement should be a component of daily operations so that the organization in charge of the industrial unit can thrive despite its rivals. Therefore, it is important for all organizational departments to promote and engage in continuous improvement [1]. Because of this, the auto industry serves as a great case study of global competition [2]. Automobile makers must continuously improve their current structures and keep them in check if they want to stay competitive and take home a larger share of future sales. In order to shield their automobiles from corrosion for years, major multinational automakers currently use cataphoresis coating processes on the body of their vehicles. Additionally, they are improving their painting procedures to avoid future painting problems. Thus, they supply products that will serve their customers for many years.

Many researchers also conduct scientific studies that will contribute to the development of these processes. Hence, in this study, the contributions of the cataphoresis coating process and primer painting processes to bonding technology were investigated. Specifically, the

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adhesion performance under fatigue resistance of metal parts on cataphoresis-coated and primer-painted samples was investigated.

When it comes to the bonding method, it would be appropriate to talk about the fracture mechanics of the adhesive in the fatigue test. As depicted in Figure 1, an elastic SLJ that is subjected to strain under two axial forces stretches by ΔL, while shear stress also occurs at the same time. The shear stress occurring along the bonding line is at its maximum level at both ends of the adhesive [3].

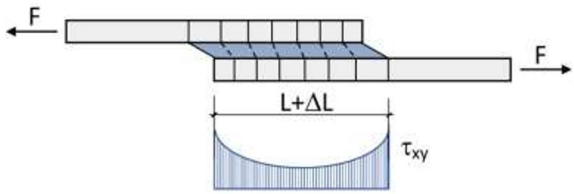

Fig. 1. Deformations and shear stresses in loaded single-lap joint (SLJ) for Elastic adherents [3].

To estimate the behavior of adhesives to use in further works, finite element models can be developed. One of the studies about finite element modeling of adhesive joints followed a way that the parametrization of stiffness of adhesive and related parameters [4]. In the study, different experimental results were used to validate the developed model. A different use of the finite element model is to obtain local stress values to foresee failure regions [5]. Knowing where and how failure occurs provides safety in designs. Therefore, fatigue crack initiation (FCI) may be a part of the analysis [6]. Adherent rigidity, on the other hand, affects the strength properties of single-lap joints. A related study has shown that higher rigidity of adherents increased the structural performance of adhesive joints [7]. Material models also affect stresses on adhesives. Considering fatigue life, a more realistic material model for the investigated problem may be a necessity. The material model effects on SLJ, for instance, become important when multiaxial stress distribution occurs, and the linear material model may be insufficient [8]. Hence, in this study, it has been investigated fatigue life of single lap joints by finite element model in accordance with experiments in reference [9].

2 Models and simulation

2.1 Materials

In this study, an unalloyed steel sheet plate of DC01A quality, which has dimensions of 0.8 (thickness) [mm] x 25(width) [mm] x 110(length) [mm] which is easy to cold-form and join and conforming to the European standard EN 10130: 2006 was used. This type of steel is frequently used in the automotive industry, especially in the vehicle body, outside of the critical load-bearing areas on the vehicle chassis. The adhesive bonding method was used to join the samples. The surface properties of the samples, which were joined by the adhesive bonding method, were collected in three different variants. Thus, the number of variants to be examined is specified in a total of three variants as indicated next.

Variant – 1: It was combined with different bonding thicknesses specified in its natural state without applying any paint or coating to the surface of the samples. There is no coating or paint on the surface of the samples to be adhered to in this group. Samples are bonded together in their natural state.

Variant – 2: 30 µm primer paint was applied to the surface of the samples in this group. Primer-painted samples were joined by bonding method in different thicknesses. These samples were conceived as a car body painted with primer. Thus, the data obtained from the samples in this group will give information about the adhesion performance in a primed body of the vehicle.

Variant – 3: The thickness of 20 µm cataphoresis coating process was applied to the surface of the samples in this group. Samples coated with cataphoresis were joined by the bonding method in different thicknesses. These samples were conceived as a car body coated with cataphoresis processes. Thus, the data obtained from the samples in this group will give information about the adhesion performance in a coated with cataphoresis process body of the vehicle.

Adhesive type should be selected according to the material to be joined. As adhesives Epoxy and polyurethane are used in this study. These adhesives constitute either a rigid connection or an elastic connection, respectively. Additionally, to absorb the vibrations caused by the dynamic loads that the steel vehicle body is affected by in different road conditions and to give it flexibility, a polyurethane-based, moisture-curing Sikaflex 252 adhesive is used as the bonding element.

2.2 Finite element model of fatigue analysis of main SLJ study

In order to obtain a finite element model of fatigue life of the considered problem [8], a commercial software package, ANSYS was used. To estimate fatigue life, S-N curves (stress cycle) were used to fit above-given data. Tabular data were provided to the fatigue module, and after various scaling and transition operations on alternating stresses and with the identical cycles obtained from the experimental investigation, an approximation was achieved. The following section includes S-N curves and some comments about them.

Figure 2 shows uncoated plates and their joint geometry. The middle of the plate has 2mm of adhesive. Contact interactions between the adhesive and the bonded plates were established. Only the adhesive's failure and its fatigue life were visible in this fashion, not the plates' failure. Mesh architecture is depicted in Figure 2. The mesh element is a finite element with a quadratic hexahedral shape. Because quadratic hexahedral mesh elements provide superior precision in solutions and occasionally match analytical solutions, they were chosen as the mesh element. In Figure 2, boundary conditions are also provided. Remote displacement, denoted by the letter B, limits movement in all axes and rotations but the y-axis. Frictionless supports placed on plates limit the Y-axis. It serves as a safeguard against boundary-based singularities. Forces applied to a single-lap joint are anticipated to have a 300N fatigue life. Fatigue study was carried out using the YZ component of shear stress and the ASME elliptical mean stress theory.

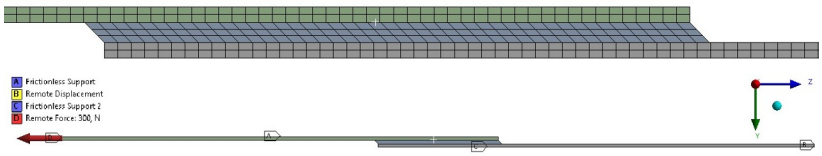

Fig. 2. Zoomed screenshot of model of single-lap joint without coating and painting, its mesh structure and boundary conditions.

Fatigue loading vs. fatigue life plots were produced using the original study [9]. To create a fatigue analysis model using the finite element approach, the ones that highlighted fatigue behavior seen in broken specimens were selected. Table 1 displays the applied fatigue loading vs. fatigue life cycles of these circumstances, which are 2mm and 6mm thick adhesives.

Table 1. Fatigue loadings and corresponding fatigue life cycles.

Type	Experimental [9]
±0.3kN (2mm primed specimens)	4998
±0.3kN (2mm cataphoresis app. specimens)	9025
±0.3kN (6mm primed specimens)	4226
±0.3kN (6mm cataphoresis app. specimens)	2001

Primed specimens have lower fatigue life against cataphoresis-applied specimens (2mm thick adhesive). As it is stated in Table 1, primed surface and cataphoresis applied specimens have close fatigue life to reach their usage limitation. From the original study, as we know, the increase in adhesive thickness closes the gap between different surface applications' effect on strength.

2.3 Numerical accuracy

A study [5] was chosen from the literature and some examples were reproduced to demonstrate the effectiveness of the method used in fatigue analysis. The issue under consideration has an adhesive layer that is perpendicular to the specimens. The paper includes SLJ experimental and numerical analysis. The original work followed a similar methodology, obtaining shear stress vs. fatigue life curves using experiments. The original study's Type B and Type E names were retained as the testing instances for numerical correctness.

3 Results

This section of the fatigue analysis findings shows the equivalent alternating stress based on the shear stress along the tearing direction and the S-N curves of the selected stress component.

3.1 Main study

In Fig. 3 primed surface specimen's stress distribution gives a similar trend as failure occurring on the corners of the adhesive. In Fig. 4, 2mm thick adhesive bonded cataphoresis applied surface specimen's stress distributions can be found.

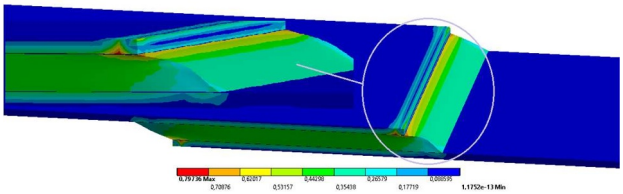

Fig. 3. 2mm thick adhesive bonded primed surface specimen's equivalent stress distribution with ±300N fatigue loading.

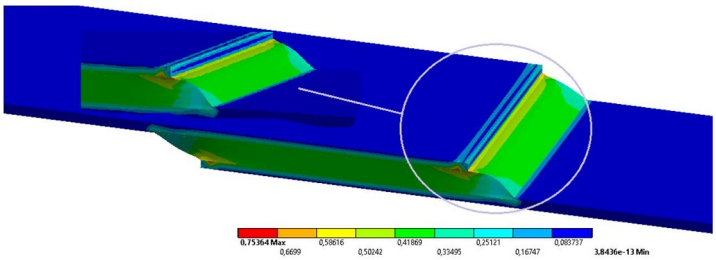

Fig. 4. 2mm thick adhesive bonded cataphoresis applied surface specimen's equivalent stress distribution with ±300N fatigue loading.

A 6 mm thick adhesive attached SLJ with prepared surface and cataphoresis applied surface specimens is another scenario that was specifically chosen in the original analysis. Failure zones in Fig. 5 highlighted the need for a deeper knowledge of adhesive behavior as layer thickness increases. Fig. 5 a and b demonstrate 2 mm thick adhesive attached SLJs with primed surfaces and surfaces treated with cataphoresis. We can infer that the corners of the adhesives were where the failure occurred.

Fig. 5 (a) 2mm thick and (b) 6mm thick adhesive bonded SLJ with primed surface and cataphoresis applied surface specimens' tearing presentation, respectively (Baykara 2023).

In Fig. 6 and 7, stress distribution of these models is shown to compare with experimental failure. Numerical results are accordance with experiment. Looking at numerical results of 6mm adhesive bonded SLJ's and experimental failure regions, it can be concluded both primed surface specimen and cataphoresis applied surface specimen have similar behaviour before failure (In Fig 5b, respectively). Adhesives begun to elongate in numerical analyses as they are being curved. It also happened in experiment.

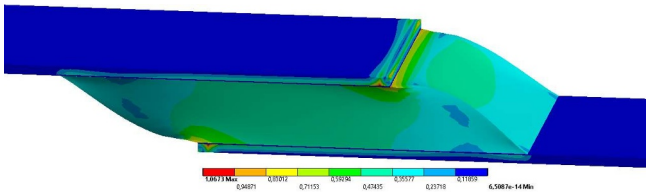

Fig. 6. 6mm thick adhesive bonded primed surface specimen's equivalent stress distribution with ±300N fatigue loading.

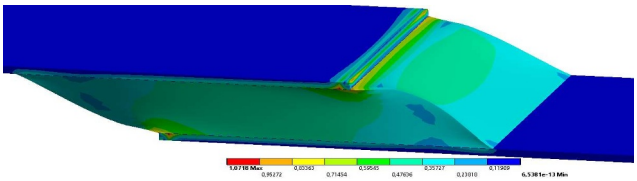

Fig. 7. 6mm thick adhesive bonded cataphoresis applied surface specimen's equivalent stress distribution with ±300N fatigue loading.

3.2 Numerical accuracy correction

Figure 8 illustrates how the stress distributions from the finite element fatigue analysis are in agreement with the results of the experiment from the original study. This correlation relates to adhesive separation from the adherent's surface without any remaining adhesives. Figure 8 shows that the stress distribution is nearly uniform, leading to uniform failure.

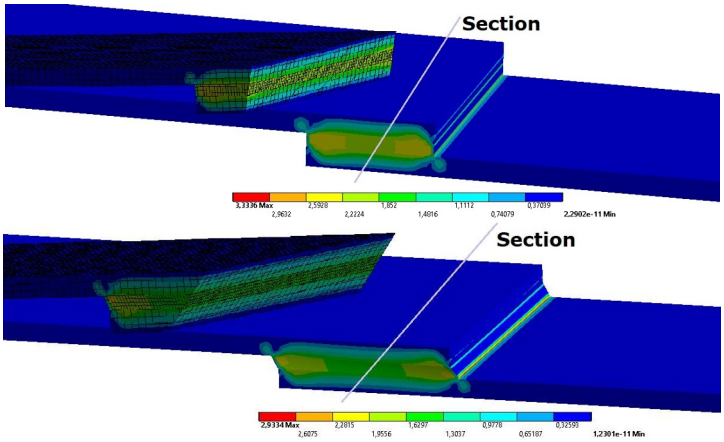

Fig. 8. Stress distributions of numerical accuracy study, Type B at the top and Type E at the bottom.

4 Conclusion

In this study, the fatigue resistance of different bonding methods including adhesive joints with various coating and adhesive thicknesses combined with adhesive techniques was simulated by finite element analysis. When optimizing the weight and performance of SLJ structures, a finite element model of this type of problem will provide flexibility.

The S-N curve for surface specimens subjected to cataphoresis has the same alternating stresses as primed surface cases, but naturally different life cycles. This manner gave almost the same experimental results. This indicates that the developed finite element model has good accuracy in the estimation of related instances (Table 2). Uncoated specimens served as the S-N curve's foundation. This allowed for the creation of coated specimen curves by scaling solely the stress values from uncoated specimens.

Table 2. Main study's comparison between experimental and FEA fatigue life results.

Type	Experimental [9]	FEA (Current)
2mm Adhesive Layer- Primed Surface	4998	4997».4
2mm Adhesive Layer- Cataphoresis Surface	9025	9022».5
6mm Adhesive Layer- Primed Surface	4226	4225».1
6mm Adhesive Layer- Cataphoresis Surface	2001	2000».9

Testing numerical accuracy proved our finite element modeling to be in the safe zone within the borders of the experimental study (Yi-Ming and Wei 2012).

Obtained results from the finite element model will give an estimation for future SLJ studies with different configurations.

5 Acknowledgements

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