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CRACK GROWTH SIMULATIONS IN ADHESIVELY BONDED JOINTS

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Keywords

Fatigue crack growth, fracture toughness, adaptive meshing

Abstract

Due to the important advantages of adhesive joints, such as their suitability for multi-material designs, their use has been increasing in the last decade. Determining the fracture behavior of structural adhesive bondings is essential for structural durability. In crack propagation analyses, adaptive meshing has drawn considerable attention because of its improvements in terms of complex preprocessing and time management. This paper presents a recently introduced separating morphing and adaptive remeshing technology (SMART) innovative crack growth simulation for adhesively bonded joints, considering static and cyclic cases. For the static case, an R-curve was obtained for the bonding joints of carbon steel and Araldite 2015. For the cyclic case, the Carbon Fiber Reinforced Polymer (CFRP) bonding joints were analyzed under constant-amplitude loading conditions. The crack-propagation rate and the number of cycles were estimated. Crack propagation simulations were validated using experimental data. Acceptable agreement was achieved between the experimental and estimated results.

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YAPIŞTIRMA BAĞLANTILARINDA SMART YÖNTEMİ İLE ÇATLAK İLERLEME SİMÜLASYONLARI

Anahtar Kelimeler

Yorulma çatlağı ilerlemesi, kırılma tokluğu, adaptif ağ yöntemi

Öz

Yapıştırma bağlantılarının çoklu malzeme tasarımı uygulamalarında kullanılabilmeleri gibi önemli avantajları nedeniyle son on yılda kullanımları artmıştır. Yapıştırma bağlantılarının yapısal bütünlüğü için kırılma davranışının belirlenmesi elzemdir. Çatlak ilerleme analizlerinde, karmaşık ön işleme ve zaman yönetimi açısından önemli iyileştirmeler sunması nedeniyle adaptif ağ yöntemi ilgi çekmektedir. Bu çalışma, yapıştırma bağlantılarında statik ve yorulma durumlarını dikkate alarak yeni bir çatlak ilerleme simülasyonu yöntemi olan ayırmalı şekillendirme ve adaptif yeniden ağ oluşturma teknolojisini (SMART) tanıtmaktadır. Statik durum için, karbon çeliği ve Araldite 2015'ten oluşan yapıştırma bağlantılarında R-eğrisi elde edilmiştir. Yorulma durumu için, karbon fiber takviyeli polimer (CFRP) yapıştırma bağlantıları sabit genlikli yükleme koşulları altında analiz edilmiştir. Çatlak ilerleme hızı ve çevrim sayısı tahmin edilmiştir. Çatlak ilerleme simülasyonları deneysel veriler kullanılarak doğrulanmıştır. Deneysel ve simülasyon sonuçları arasında kabul edilebilir bir uyum elde edilmiştir.

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1. Introduction

Adhesively bonded joints are one of the most promising joining methods compared to conventional methods, such as welding and rivets. Although the evaluation of the behavior of bonded joints according to the classical approach is a well-known field in the literature, assessment using fracture mechanics methods has drawn increasing attention. It has been an important research area over the past decade (Jones and Kinloch, 2015). It has not yet been fully adapted by design engineers in terms of the design and determination of the life of engineering components. Therefore, it can be considered a relatively new field. Adhesive joints are widely preferred in industries such as automotive, aeronautics, and shipbuilding, and their use is increasing regularly (Zuo and Vassilopoulos, 2021). For example, the main reason for its increased use in the automotive industry is the reduction in the weight of automotive components without a significant reduction in mechanical performance. In this regard, steel and multi-material designs of modern materials, such as titanium, aluminum, magnesium, and composites, are widely preferred because multi-material designs provide a significant advantage in terms of weight decrease (Chen, Avery, Su and Kang, 2017). Another important use of composites is in aeronautic and shipbuilding applications (Saleh, Budzik, Saeedifar, Zarouchas and Teixeira De Freitas, 2022). It is not possible to effectively join composites and other modern engineering materials using traditional methods, such as rivets and welding. This is one of the most prominent advantages of the adhesive joints. In addition, it provides important advantages such as relatively favorable load transfer paths, good fatigue strength, and aesthetics, being suitable for the use of thin materials, low-stress distribution, being relatively economical, and easily adaptable to automation (Korta, Młyniec, Zdziebko and Uhl , 2014).

Fatigue failure in engineering applications, that is, failure of components at stress levels lower than the yield strength due to crack propagation under cyclic loading conditions, is the most typical failure mechanism (Quan and Alderliesten, 2022). Therefore, it is very important to determine the fatigue and fracture behaviors of adhesive joints using fracture mechanics methods. Owing to variables such as various geometries, loading rate, loading mode, and joint parameters, the determination of the fracture behavior of the joint requires long experimental practice and is therefore challenging (Jones, 2014). Banea, Da Silva and Campilho (2015) showed that fracture toughness increased as the thickness increased in the 0.2-2 mm adhesive thickness range. However, increasing the adhesive thickness causes a decrease in lap shear strength. For epoxy (Figueiredo, Campilho, Marques, Machado and Da Silva, 2018) and acrylic (Sekiguchi and Sato, 2021) adhesives, it has been reported that increasing the adhesive thickness leads to an increase in fatigue toughness. The effects of various geometries (Costa, Carbas, Marques, Viana and Da Silva, 2017), different loading types, that is, Mode I, Mode II, and Mixed Mode (Mode I + Mode II), and different R ratios on the static (Monteiro et al., 2020) and fatigue (Rocha et al., 2020) fracture behaviors of the structural adhesives were investigated. Higher stress amplitudes cause faster crack propagation, resulting in a lower life of the components. It was also observed that the fatigue crack propagation rate decreased as crack extension increased (Huang et al., 2013). Linear elastic fracture mechanics (LEFM)-based or J-integral-based, that is, elastic-plastic fracture mechanics (EPFM) techniques, are used to determine the fracture behaviors of adhesive joints. The use of LEFM for fatigue crack growth (FCG) in adhesively bonded joints is a good prediction method, although the underlying physics have not been fully comprehended (Pascoe, Alderliesten and Benedictus, 2017). However, significant deviations may occur in the LEFM estimates depending on the fracture process zone size, and it has been suggested to use the J-integral in such cases (Sarrado, Turon, Costa and Renart, 2016).

The use of the finite element method (FEM) to examine the fracture behavior of cracked components has attracted increasing attention. The Cohesive Zone Method (CZM) is widely used to analyze the fracture behavior of structural adhesives (Campilho, Banea, Pinto, Da Silva and De Jesus, 2011; Rosas, Campilho and Moreira, 2021; Silva, Peres, Campilho, Rocha and Silva, 2023). The model was resolved by defining special interface elements in the region where the crack was located. However, in these models, every crack propagation step requires crack tip re-meshing, that is, a new mesh model needs to be reconstructed, which increases the computational costs and complicates the model (Funari, Lonetti and Spadea, 2019). Therefore, the use of adaptive mesh methods has attracted increasing attention. The newly introduced Ansys's SMART module eliminates the long and complex re-meshing process. As the crack extended, re-meshing was performed automatically around and adjacent to the crack tip (Alshoaibi, 2021). The validity of the SMART procedure has been demonstrated in different types of cracks (Gupta, Sun and Bennett, 2020; Matvienko, Razumovskii and Fedorov, 2021), fatigue crack growth trajectories (Lee and Lu, 2022), and fatigue crack growth in weld transitions (Kowalski and Rozumek, 2019).

Conducting experiments for every boundary condition in engineering applications is considerably time-consuming and costly. Therefore, the finite element method serves as a powerful tool. Modelling of structural adhesives with CZM is very common in the literature. However, analyses of three-dimensional crack propagation with the Cohesive Zone Model (CZM) typically require a rather complex pre-processing stage and have high time/resource demands. Furthermore, it employs damage parameters that are quite challenging to obtain experimentally. On the other hand, the adaptive mesh method can offer faster solutions with a simpler model structure, particularly in complex three-dimensional geometries. This study aims to investigate the static and cyclic behavior of structural adhesives using the SMART procedure, which is an adaptive mesh method. The applicability of the SMART procedure as an alternative to the CZM in adhesive joints has been investigated. A double cantilever beam (DCB) geometry type was modelled, and stable crack and fatigue crack propagation were analyzed by defining different adhesives. In this regard, the static and cyclic behaviors of adhesive joints were examined and compared with experimental data.

2. Crack Growth Simulations

In this study, two different cases were analyzed with the SMART procedure. In the first case, the static state was evaluated under mode I loading conditions. The adhesive joint was modeled using a structural epoxy adhesive and C45E plain carbon steel adherend. The critical energy release rate (G_{Ic}) and total crack propagation were analyzed and compared with experimental results from the literature. In the second case, the cyclic loading conditions were evaluated under mode I loading conditions. The adhesively bonded joint is modeled from the structural epoxy adhesive and carbon fiber reinforced plastic (CFRP) composite. The crack growth rate (da/dN), total crack propagation, and number of cycles were analyzed and compared with experimental data obtained from the literature. Laboratory conditions were based on both case analyses.

2.1 Theoretical Background

Engineering components have macro-or microscale defects that occur during their production and service. The failure behavior of components with crack-like defects is difficult to determine using the classical approach; therefore, a fracture mechanics approach is necessary. The concept of fracture mechanics becomes more complex with the effects of many parameters such as the location and size of the crack, geometry, and loading mode. Therefore, the fracture toughness obtained in the specimen geometries cannot always be exactly transferred to the actual engineering component geometries. The LEFM concept is one of the most widely used fracture mechanics methods for investigating the behavior of adhesively bonded joints. LEFM assumes that elastic effects dominate the stress-strain regions at the crack tip and adjacent regions with very limited plasticity effects. In this study, simulations performed using the SMART procedure were also based on the LEFM. The fracture behavior of an adhesively bonded component is generally characterized by LEFM parameters, such as the stress intensity factor K or energy release rate G. Determining the fracture toughness (K_{Ic} or G_{Ic}) is generally not sufficient for engineering applications because, in real-life applications, components often work under cyclic loading conditions. The relationship between G and K and its solution for the DCB geometry are defined in Equation 1 (Anderson, 2017):

$$G = \frac{\pi\sigma^2 a}{E} = \frac{K_I^{\,2}}{E'} \tag{1}$$

where E is Young's modulus, E'=E for plane stress conditions, E'=E/(1-ν^2) for plane strain conditions, σ is the stress, a is the crack length. The calculation of the stress intensity factor K_I is performed via the interaction integral method defined in Equation 2 and the angle of fatigue crack propagation is determined by Equation 3 (ANSYS, 2020).

$$I = \frac{\int_v q_{ij}\left[\sigma_{kl}\epsilon_{kl}^{aux}\delta_{ij} - \sigma_{kj}^{aux}u_{kj} - \sigma_{kj}^{aux}u_{kj}\right]}{\int_S \delta q_n dS} \tag{2}$$

$$\theta = cos^{-1}\frac{3(K_{II}^{max})^2 + (K_I^{max})\sqrt{(K_I^{max})^2 + 8(K_{II}^{max})^2}}{(K_I^{max})^2 + 9(K_{II}^{max})^2} \tag{3}$$

Where σ_{ij},ε_{ij},u_i are components of stresses,strains and displacements, respectively; σ_{ij}^{aux},ε_{ij}^{aux},u_i^{aux} are components of stresses, strains and displacements of the auxiliary field, respectively; qi are crack extension vector components. The subscripts under K represent mode-I and mode-II fracture. Under cyclic loading conditions, the Paris-Erdogan equation is often used (Paris and Erdogan, 1963). As defined in Equation 4, Paris-Erdogan revealed that crack propagation per unit cycle, that is, the crack growth rate da/dN expression, was related to G. Crack propagation under cyclic loads was defined in three stages. In the first stage, the crack extension begins. The second stage is the stable crack propagation stage, which covers most of the life before the fracture. This stage was also known as the Paris Regime. In the third stage, the crack propagation became unstable, and fracture occurred with a sudden increase in G.

$$\frac{da}{dN} = Cf(G)^n \tag{4}$$

$$f(G) = \Delta G = G_{max} - G_{min} \tag{5}$$

For f (G), one of the definitions specified in Equation 5 is typically used. Where G_{min} is the energy release rate at the minimum load and G_{max} is the maximum load. In this paper, G_{max} was considered to be compatible with the experimental study.

2.2 Materials and Specimen Geometries

For the first case, the structural epoxy adhesive Araldite 2015 and adherend

C45E plane carbon steel were modelled. In the other case, the structural epoxy adhesive Loctite EA 9395-9396 and CFRP (Hexcel 8552) as the adherend were modelled. The mechanical properties of the materials used in the models for the two cases are listed in Table 1. The Paris-Erdogan parameters obtained experimentally (Floros and Tserpes, 2019) under cyclic loading conditions are listed in Table 2. The DCB-type specimens were modelled for both cases. The DCB specimen geometries are presented in Figure 1 for the first case and in Figure 2 for the second case. All dimensions are in millimeters. The geometric dimensions and material properties are based on the manufacturer's data and literature. The adhered CFRP material was modeled as a solid to simplify the crack propagation simulation and reduce resource/time requirements.

Table 1. Mechanical Properties of the Materials Modelled in the Simulations

Case	Material	Young's Modulus (GPa)	Poisson's Ratio	Tensile Yield Strength (MPa)	Tensile Failure Strength (MPa)	Shear Modulus (GPa)	Critical Energy Release Rate (N/mm)
Static (Lopes, Campilho, Da Silva and Faneco, 2016)	Adhesive	1.85	0.33	13	22	0.56	0.43
	Adherend	204	0.3	279	347	78	
Fatigue (Thäsler, Holtmannspötter and Gudladt, 2019)	Adhesive	3.35	0.35	-	56.8	1.5	-
	Adherend	164	0.3	-	2724	63	

Table 2. Paris-Erdogan Parameters Were Used İn The Simulation (Floros and Tserpes, 2019)

Paris-Erdogan Parameters	
C	0.47
n	7.22

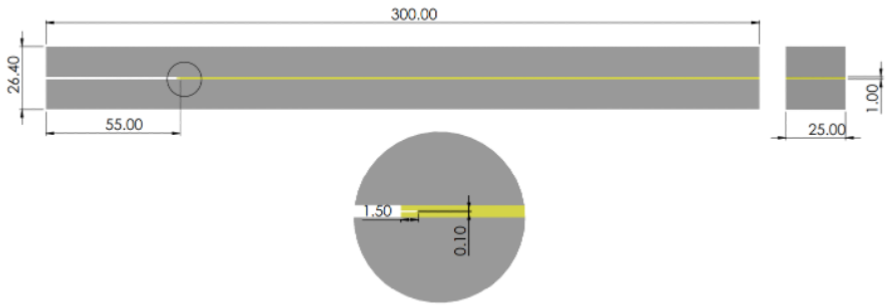


Figure 1. Specimen Geometry For The Static Case, According to (Lopes et al., 2016).

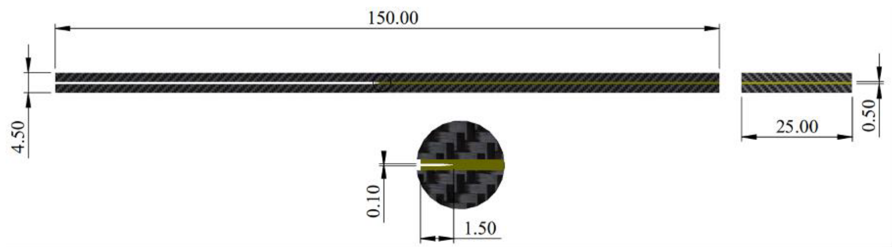
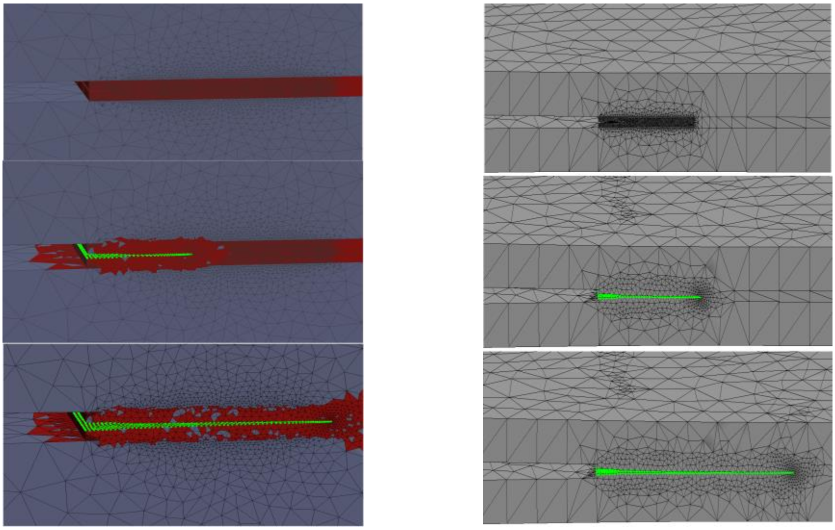


Figure 2. Specimen Geometry for the Cyclic Case, According to (Floros and Tserpes, 2019).

2.3 Crack Growth with SMART Procedure

Although various experimental and numerical methods are extensively used for the evaluation and solution of engineering problems, adaptive mesh and extended finite element methods (XFEM) are drawing more attention as alternative solutions. The experimental and finite element methods were complementary to each other. Finite element applications will gain more importance owing to the cost and time issues of the experimental methods. The SMART procedure, developed and introduced by ANSYS Inc., has introduced many innovations in the field of fracture mechanics. With SMART, crack propagation simulations in 3D geometries can be performed effectively in terms of process time. Since geometry is a parameter that directly affects the fracture behavior of engineering components, it is not always possible to model real and complex geometries of components in 2D, so effective modelling of 3D geometries is essential for engineering applications. In addition, SMART shortens the need for post-processing for designers and researchers by using the unstructured mesh method (UMM) with its tetrahedral mesh elements and significantly minimizes the complex mesh structure and re-meshing time. With SMART, re-meshing is automatically conducted at the crack tip and adjacent to the crack propagation in each substep time interval. This provides significant flexibility and saves time in terms of complex preprocessing transactions. Figure 3 shows the crack propagation and re-meshing at the crack tip and adjacent under static and cyclic conditions, respectively. Cracks with different shapes (such as semi-elliptical and pre-meshed) can be simulated using SMART technology. However, this method has some significant limitations. In this study, it is assumed based on experimental data that the crack will propagate only through the adhesive. However, this assumption is not always valid in real applications. Moreover, the effects of defects such as local air voids and surface roughness present in adhesive joints were not considered in the conducted simulation.

A pre-meshed crack structure was used for both the analyses. The crack tip and adjacent were improved using the sphere of influence method. For the solution, the contour was determined as 6, and the crack tip, lower, and upper surfaces were defined for the pre-meshed crack, and a separate coordinate system was defined for the crack. The mesh structure created in the DCB specimens for the static case is shown in Fig. 4. The mesh structure is directly related to the precision of the obtained results. The mesh structure of a region/model can be determined by mesh quality criteria, such as aspect ratio, skewness, and orthogonal quality. Since tetrahedral element type was used in the simulation, the skewness mesh quality criterion was preferred. According to the skewness mesh quality criterion, the mesh quality increases as the average skewness value approaches 0 with a minimum of 0 and a maximum of 1. In the models used for both cases, meshing was performed with UMM and tetrahedral SOLID187 elements with an average size of 2 mm. A very fine mesh with an average size of 0.05 mm was applied at the crack tip and adjacent regions. The DCB specimens modelled for the static case had 651357 nodes and 449556 elements. The overall mesh structure has an average value of 0.2 according to the skewness mesh quality criterion. The skewness of a mesh structure indicates how close it is to the ideal shape or form. In general, low orthogonal or high skewness values are not recommended. The SOLID187 element, a 10-node higher-order three-dimensional finite element, is optimally designed for the analysis of solid structures. SOLID187 exhibits quadratic displacement characteristics, making it particularly well-suited for accurately representing irregular mesh geometries. This element is characterized by the presence of ten nodes, each offering three degrees of freedom, enabling translation along the nodal x, y, and z axes.



(a) **(b)**

Figure 3. Re-Meshing at the Crack Tip And Adjacent With Crack Propagation, for Static (a) and Cyclic (b) Cases, Respectively

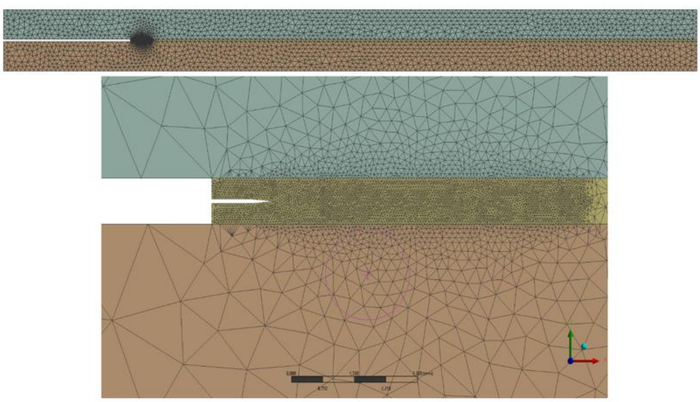


Figure 4. General and Crack Tip Mesh Structures in DCB Specimen for the Static Case

The DCB specimens modelled for the cyclic case had 486266 nodes and 358919 elements. The skewness mesh quality criterion had an average value of 0.28. The overall mesh structure of the DCB specimen in the cyclic case is shown in Figure 5. In the crack propagation simulations performed for both cases, a gradual displacement was applied, and a solution was conducted in 150 sub-steps. A 0.0113 mm/sub-step displacement was applied for the static case, whereas a 0.0073 mm/sub-step displacement was applied for the cyclic case. Crack growth simulations were carried out under a constant amplitude load ratio of R=0.1 for cyclic loading. The boundary conditions of crack growth simulation models prepared for the static and cyclic cases are shown in Fig. 6. In this study, the principles of research and publication ethics have been adhered to.

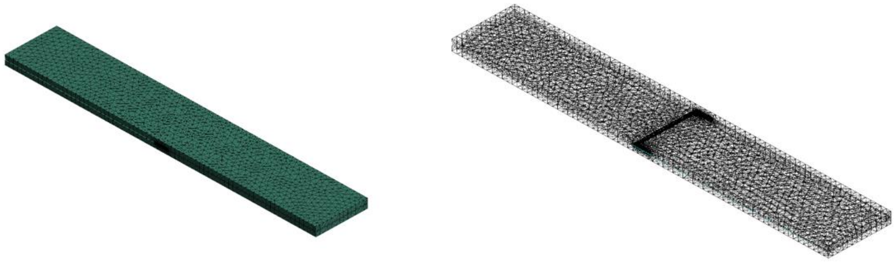


Figure 5. General Mesh Structure İn DCB Specimen For The Cyclic Case

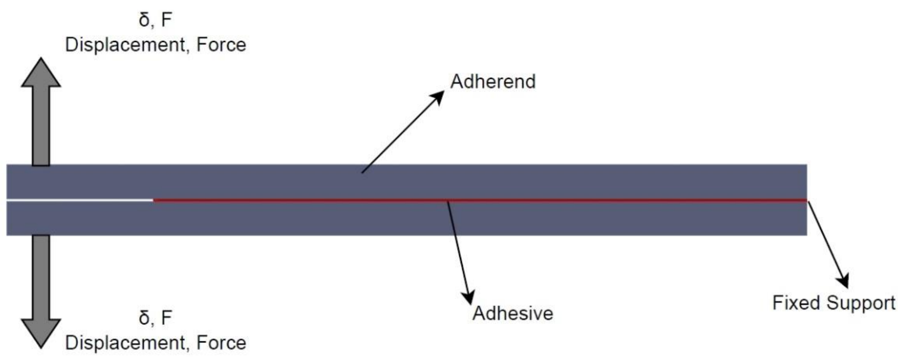


Figure 6. Schematic Representation of Boundary Conditions in Crack Growth Simulation Model

3. Results and Discussions

Two different crack propagation simulations were performed using the SMART procedure for the static and cyclic cases. In the model at mode I loading for the static case, the fracture toughness (G_{Ic}) of Araldite 2015 was defined as 0.43 N/mm. G_{Ic} is the critical level at which the crack propagation begins. A total of 5.45 mm crack propagation occurred in the finite element analysis. The R-curve obtained for the static case is shown in Fig. 7. When compared with the experimental data (Lopes et al., 2016), it was observed that the results obtained from the analysis converged with the experimental results. After the G_{Ic} level for crack propagation is exceeded, the crack starts to propagate; however, as can be seen from the results, the G level required for crack propagation does not increase linearly. A stable propagation was observed after approximately 5 mm of crack propagation. This is in agreement with the experimental data. When the data obtained from the finite element analysis were compared with the experimental data, the error rate reached a maximum of 20%, while the average was 7%. In finite element analysis, the ideal situation is modelled; however, in experimental practice, deviations may occur owing to adhesive issues, defects, and crack arrest (Campilho, Moura, Banea and Da Silva, 2015). Therefore, the results obtained from the finite element analyses performed using the SMART procedure were within acceptable deviations when compared with the experimental results.

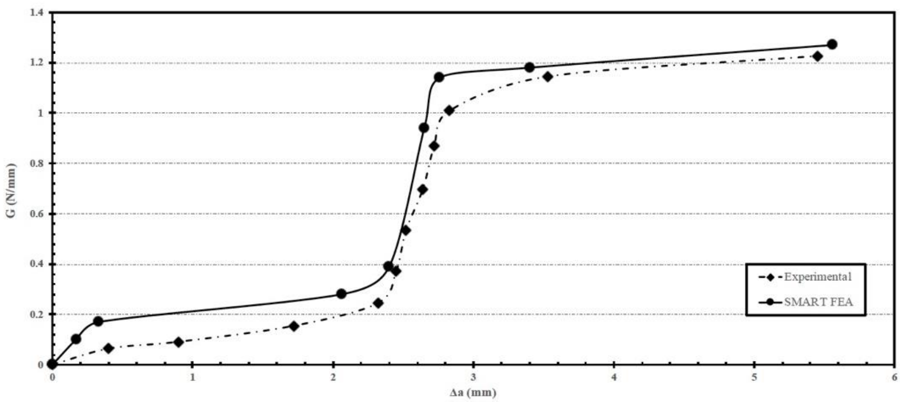


Figure 7. Comparison With the R Curves for the Static Case and the Experiment (Lopes et al., 2016)

A comparison of the crack propagation with the experimental data (Floros and Tserpes, 2019) against the number of cycles obtained from the crack propagation simulation performed for the cyclic case is shown in Figure 8. As the number of cycles increased, the crack propagation decreased. In addition, the crack propagation did not increase linearly. From this analysis, a total crack propagation of approximately 11.7 mm was obtained. The experimental data were separated using finite element analysis at the initial stage of crack propagation. In the finite element analysis, the crack extended much faster than that in the experimental application. This increased the deviation rate. However, when evaluated as a whole, consistent results were obtained in terms of the number of cycles and the total crack propagation parameters.

The fatigue crack growth behavior obtained under constant amplitude R=0.1

mode-I loading conditions is presented in Figure 9 on a log-log scale. Gmin was not considered, and $G_{max}$was used as a basis for compatibility with the experimental results, as previously defined in Equation 3. Large scatterings have occurred in the maximum energy release rate G_{max} curve corresponding to the obtained crack propagation rate da/dN. While the conducted simulation was able to more accurately predict sections with high crack propagation rates, it was unable to achieve sufficient success at low crack propagation rates. There could be many reasons for this. For instance, local air voids in the adhesive could be much more effective at low crack propagation rates. The way the adhesive is applied and the condition of the surface also have a significant impact on the results obtained experimentally. As the crack propagation simulations conducted examined the ideal situation, scatterings can occur in the results obtained. The Paris-Erdogan parameters C and n obtained experimentally have a significant place in the accuracy of the simulation. Wide scatterings in experimental data can affect the accuracy of these parameters.

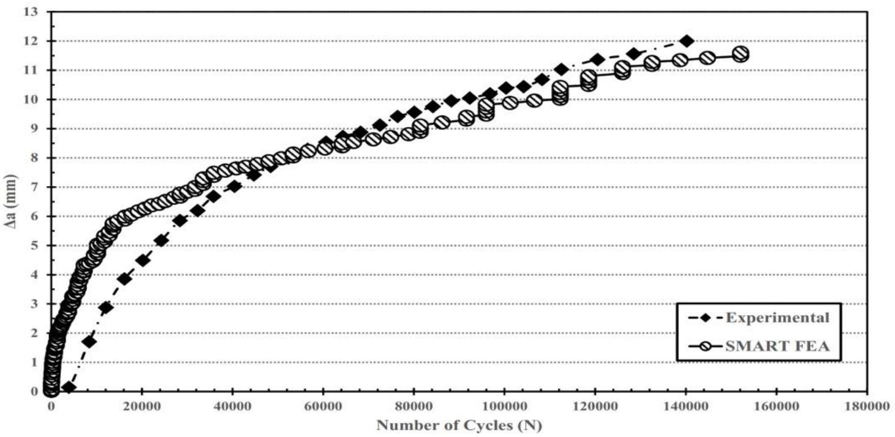


Figure 8. Comparison With Fatigue Crack Propagation and Experimental Data (Floros and Tserpes, 2019) for the Cyclic Case

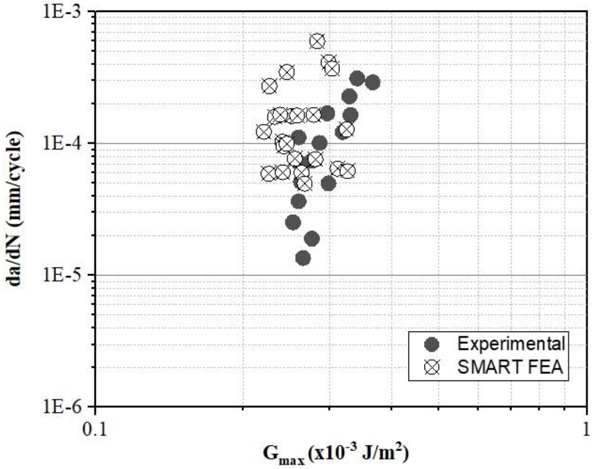


Figure 9. Comparison With Fatigue Crack Growth Rate And Experimental Data (Floros and Tserpes, 2019) for the cyclic case

5. Conclusions

In this study, the SMART procedure, a newly developed adaptive meshing method, was examined. Crack propagation simulations in bonded joints were successfully performed using the SMART procedure and validated using experimental data. Crack propagation occurs in 3D throughout the simulation, and with it, the sensitive crack tip region mesh structure changes and adapts. The finite element method is a powerful tool for determining the effect of complex interactions on the fracture behavior of engineering components. Although experimental methods are the most reliable for determining the fracture behavior of adhesively bonded joints, it is not realistic in terms of cost and time management to experiment for each combination of geometries and joints. Therefore, it became necessary to examine different crack types in complex geometries using 3D finite element simulations. Under mode I loading conditions, valid crack propagation simulations were performed for two different cases: static and cyclic. The R-curve obtained for the static case was compared with the experimental data, and consistent results were obtained. Although the crack propagation for the cyclic case was faster than the experimental data at the beginning, the deviation rate increased; however, the experimental data were generally in agreement with the experimental data. If it remains within the elastic limits, SMART is a highly accurate tool, but its validity should be carefully questioned in situations where plasticity effects are more effective. This is one of the biggest disadvantages of this technology under the current conditions. While the SMART procedure in adhesive joints offers a simple analysis structure and fast analysis solution in three-dimensional complex geometries, we believe that the results obtained need to be carefully examined. Adhesives can exhibit behaviors ranging from brittle to viscoelastic or plastic. We believe that the LEFM approach can also be used within certain error scatters in crack propagation analyses in adhesive joints. However, the character of the plastic zone occurring at the crack tip and the complex stress structure formed in the adhesive can significantly complicate the crack propagation analyses. This situation can limit the accuracy of the LEFM approach. Hence in future studies, investigating different types of adhesives and adherends, and different crack geometries in the application of the SMART procedure to adhesive joints will be decisive for the accuracy of the method.

Nomenclature

a	Crack Length
C	Paris-Erdogan Exponent
CFRP	Carbon Fiber Reinforced Polymer
CZM	Cozehive Zone Method
da/dN	Crack Growth Rate
DCB	Double Cantilever Beam
EPFM	Elastic-Plastic Fracture Mechanics
ε	Strain
FCG	Fatigue Crack Growth
FEM	Finite Element Method
G	Energy Release Rate
G_{Ic}	Critical Energy Release Rate or Fracture Toughness
G_{max}	Energy Release Rate at Maximum Load
G_{min}	Energy Release Rate at Minimum Load
I	Interaction Integral
K	Stress Intensity Factor
K_{Ic}	Critical Stress Intensity Factor or Fracture Toughness
LEFM	Linear Elastic Fracture Mechanics
n	Paris-Erdogan Constant
σ	Stress
SMART	Separating Morphing and Adaptive Remeshing Technology
u	Displacement

UMM Unstructured Mesh Method

X-FEM Extended Finite Element Method

θ Angle of Crack Propagation

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