Elsevier Editorial System(tm) for International Journal of Fatigue
Manuscript Draft

Manuscript Number:

Title: Unified methodology for the prediction of the fatigue behaviour of adhesively bonded joints.

Article Type: Research Paper

Section/Category:

Keywords: Damage mechanics; fatigue; strength degradation; backface strain; adhesive joint.

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Manuscript Region of Origin: Europe

Unified methodology for the prediction of the fatigue behaviour of adhesively bonded joints.

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Abstract

A unified model is proposed to predict the fatigue behaviour of adhesively bonded joints. The model is based on a damage mechanics approach, wherein the evolution of fatigue damage in the adhesive is defined as a power law function of the micro-plastic strain. The model is implemented as an external subroutine for commercial finite element analysis software. Three dimensional damage evolution and crack propagation were simulated using this method and an element deletion technique was employed to represent crack propagation. The model was able to predict the damage evolution, crack initiation and propagation lives, strength and stiffness degradation and the backface strain during fatigue loading. Hence the model is able to unify previous approaches based on total life, strength or stiffness wearout, backface strain monitoring and crack initiation and propagation modelling. A comparison was made with experimental results for an epoxy bonded aluminium single lap joint and a good match was found.

Keywords: Damage mechanics, fatigue, strength degradation, backface strain, adhesive joint.

1. Introduction

Bonded joints are increasing replacing conventional joints in structural applications, notably in the Aerospace, Automotive and Marine industries. This is mainly due to mechanistic advantages such as; high strength and stiffness to weight ratio and reduced stress concentrations, however, cost savings can also be made. This has lead to challenges in the field of designing such joints, especially under fatigue loading, which is the typical loading type in most structural applications. Lifetime prediction under fatigue loading is an important part of the design process and can be used to optimise the joint design and inform in-service monitoring procedures as well as indicating the safe life of the joint under various conditions. Many methods of predicting and characterising fatigue life in bonded joints have been proposed [1]; however, to date the various approaches have been limited in their functionality and applicability.

The methods of predicting fatigue lifetime can generally be classified as; total-life, Palmgren-Miner (PM) based, phenomenological based and progressive damage models. Several reviews have been published [2-3] regarding usage of these models for metals and for composite materials and more recently for bonded joints [1]. It can be concluded from these reviews that while total life based approaches are the simplest to apply; they have limited scope in the lifetime prediction of bonded joints, especially in the case of variable amplitude fatigue.

PM based models, as first proposed by Palmgren [4] and Miner [5], are also simple to apply and are used to predict fatigue lifetime under variable amplitude fatigue loading through the assumption of linear damage accumulation. However, they are generally not able to account for load interaction and load sequencing effects present in a variable amplitude fatigue loading spectrum. In addition, none of the approaches discussed so far (both total life and PM rule based) can be used to monitor the damage in the sample as only the final failure is characterised. This can be achieved through the application of phenomenological models.

Phenomenological models represent change in the strength or stiffness under fatigue loading and can incorporate factors to model variable amplitude fatigue. However, these models are highly dependent on joint specific experimental results and in the case of strength wearout require destructive experimental testing. Recent work has demonstrated the effectiveness of the strength wearout approach to predict fatigue lifetime under both constant and variable amplitude fatigue loadings [6-9]. However, a more flexible and direct method of representing fatigue degradation is through progressive damage modelling.

Progressive damage models can be either fracture mechanics (FM) or damage mechanics (DM) based. In the case of FM based models, the crack propagation phase is assumed to be dominant and is characterised by an empirical crack growth law. The most extensively used crack growth laws are based on the one proposed by Paris and Erdogan [10]. In this model the crack growth rate is defined as a power law function of stress intensity factor in the crack tip region. In the case of bonded joints, strain energy release rate is usually used instead of stress intensity factor [11-15]. A FM based approach has also been proposed for variable amplitude fatigue where a damage shift factor was used to account for load interaction effects [16]. However, the main draw-back to the FM approach is that it does not account for crack initiation prior to macro-crack growth. For example, when bonded single lap joints (SLJ) are considered, the crack initiation was found to dominate the fatigue life at high cycles [17], and in such cases the Paris law method of lifetime prediction will under predict the fatigue lifetime.

Using a DM based approach, the evolution of damage prior to macro-crack growth can be simulated. In these models the main requirement is to define a damage variable to represent the severity of material damage during fatigue loading. In the case of composite materials, models have been proposed to simulate delamination and damage in the matrix [18, 19]. These models can be characterised based on the type of damage growth law and the parameters used to define them, which include matrix crack density in the case of glass fibre reinforced plastic composites [19] and a thermodynamic potential based strain energy density in the case of carbon fibre composites [18]. To date, little on the application of DM to the fatigue life of bonded joints can be found in the literature, however Abdel Wahab et al. [20] used a

continuum damage mechanics (CDM) approach to predict the fatigue lifetime of bonded double lap joints and found this compared favourably with the FM based approach. However, no attempt was made to incorporate the CDM approach in a progressive damage model.

It can be seen that, all of the models discussed can be useful in characterising or predicting fatigue behaviour under certain conditions but that all have limited applicability and functionality, and it appears that no attempt has yet been made to propose a methodology that is widely applicable and can be used to generate all the data from the methods discussed. In this paper a unified fatigue methodology (UFM) is proposed, wherein a single damage evolution law is used to predict all the main parameters characterising the fatigue life of bonded joints. These consist of progressive damage evolution, crack initiation and propagation lives, backface strain (BFS) characterisation and strength and stiffness wearout. In this way a single damage evolution law is used to unify all previous approaches to characterising and predicting fatigue in bonded joints.

2. Unified fatigue methodology (UFM)

In this methodology a damage evolution law is used to predict the main parameters governing fatigue life. The model is described in Fig. 1. The inputs for the method are; material properties, joint geometry and boundary conditions. A small number of fatigue-life test results are required to determine the constants in the damage evolution law. Various algorithms are used to determine the different outputs as described in the following subsections.

2.1 Progressive damage modelling

The rate of damage evolution was assumed to be a power law function of the equivalent micro plastic strain, i.e.:

$$\frac{dD}{dN} = m_1 \left(\varepsilon_p\right)^{m_2} \tag{1}$$

where, D is the damage variable, which is equal to 0 for undamaged material and 1 for completely damaged material. N is the number of fatigue cycles and hence dD/dN is the damage rate. m_1 and m_2 are experimentally determined constants and ε_p is the localised equivalent plastic strain. Plastic strain was used as the parameter for damage progression in this approach as this is a convenient method of introducing a level of strain below which, damage does not occur. Also, the region of high equivalent plastic strain matches well with the region of damage observed optically in sectioned and polished samples, as shown in Fig. 2. Note that the adherend is not shown in Fig. 2(b) to aid clarity and only half the sample width is shown owing to the use of symmetry in the model. Hence, the area of maximum equivalent plastic strain indicated in the figure is in the middle of the sample width. The damage model can be implemented in commercial finite element software via an external subroutine. Eqn. 1 can be numerically integrated over each element in the model to simulate damage evolution followed by crack propagation for fully damaged elements (i.e. where D =1). Using this algorithm, the number of cycles to failure for different fatigue loads can be calculated. The constants m_1 and m_2 can be optimised based on fatigue life data for two or three different loads spanning the range to be considered.

2.2 Prediction of damage evolution and crack initiation and propagation

The immediate results of the model described in the last section are 3D maps of damage evolution and crack propagation as a function of cycles for different fatigue loads. This data is conveniently represented as plots of damage and crack length vs. number of fatigue cycles. In terms of damage, this can be viewed for individual elements or averaged over an area of interest. This information can be used to determine the location and extent of damage in the adhesive layer at any time in the fatigue life. The fatigue initiation life is defined as the number of cycles prior to complete damage of an element or the number of cycles to generate a crack of predetermined size. Once a crack has initiated, the damage in elements ahead of the crack can be used to study the size and shape of the process zone. Any overloads in the fatigue spectrum will increase damage in the elements ahead of the crack. Hence, the crack acceleration which has been

observed in the variable amplitude fatigue testing of bonded joints [7, 9, 21] can potentially be modeled using this approach, without the need for any further empirical interaction factors, as in [9, 16]. It is also interesting to note that if a visco-elastic/ plastic constitutive model was used for the adhesive, then time dependent straining would occur under load that would increase damage. This, potentially, could be used to model the creep enhanced fatigue failure of bonded joints reported in previous work [15, 22]. Hence, UFM also has the potential to unify the methods used to characterise variable amplitude fatigue and creep fatigue in adhesively bonded joints. Once a macro-crack has formed, the size and shape of the crack as a function of cycles is generated, as in the FM based methods.

2.3 Extended L-N curve prediction

Load-life (L-N) is often plotted instead of stress-life for bonded joints. This is because stress in bonded joints is extremely non-uniform and there is no simple relation between the easily measured average shear stress in a lap joint and the maximum stress. Hence, it is sensible to use load in the place of stress to define the fatigue life. The total fatigue life, N_f, can be divided into crack initiation and propagation lives as:

$$N_f = N_i + N_p \tag{2}$$

where, N_i is the number of cycles to macro-crack initiation and N_p is the number of cycles associated with crack propagation prior to complete failure. It is possible to predict both N_i and N_P in addition to N_f, from the data described in the previous section. These can be plotted as a function of fatigue load, as shown schematically in Fig. 3. The resultant plot shows the proportion of the fatigue life spent in crack initiation and propagation, in addition to total fatigue life, and has been termed an extended L-N diagram.

2.4 Strength and stiffness wearout and BFS prediction

A reduction in the strength or stiffness of bonded joints on fatigue loading is associated with an increase in damage in the adhesive. As damage in the adhesive is simulated using eqn. (1), strength and stiffness wearout can be expected. The decrease in strength of a joint owing to the modelled fatigue damage can be calculated by applying an increasing load to the joint until it fails. This can be done using an algorithm similar to the one described in section 2.1 for checking if N_f has been reached. Once the adhesive is damaged or cracked, a series of increasing loads can be applied until the model becomes unstable for the applied load. The instability in the model indicates that the joint cannot bear the applied load and thus an approximate value of the failure load (or residual strength) can be deduced. This method was found to work well in this case, however, alternative quasi-state failure criteria may also be used in a similar fashion.

In the case of stiffness wearout, at each damage increment in the model, the displacement at the loaded end of the joint for the applied maximum fatigue load can be calculated. Using this displacement and the applied load, the stiffness of the joint can easily be calculated. BFS can be calculated by measuring strain under load at any location in the joint in the same algorithm. For every increment in the damage, the average elastic strain on the back-faces of the adherend at any desired location can be calculated. This stage can be extended to include practically any other useful means of characterising fatigue damage, such as internal stresses and strains or natural modes and frequencies of vibration.

3. Implementation and experimental validation of the unified fatigue methodology (UFM)

The UFM was implemented using an external subroutine written in Python script language for the MSC Marc finite element analysis (FEA) software. The model was implemented for bonded SLJs manufactured according to British standards BS ISO (4587:2003). The adherends were 7075 T6 aluminium alloy and the adhesive used was Cytec FM 73M. The joint geometry is shown in Fig. 4. Fatigue testing was at 5 Hz with a load ratio of 0.1. Further details of the experimental work can be found in [8, 17].

3.1 Finite element details

The commercial FEA package MSC Marc was used for all the simulations. Eight noded hexahedral elements (Element 7 in MSC Marc) were used for the finite element mesh. Both material and geometric non-linearity were accounted for in the analysis. A typical mesh taken from a finite element model is shown in Fig. 5. The joint was constrained in the vertical direction at the loaded end of the joint, as shown in Fig. 6. In addition symmetric conditions (both planar and rotational) were applied enabling only a quarter of the joint to be modelled and thereby saving computation time.

Non-linear material properties were used in all the models. The Young's moduli for adhesive and aluminium alloy were 2GPa and 70GPa respectively. The Mohr-Coulomb model [23] was used for the adhesive and linear elasticity was assumed for the aluminium alloy as no plastic deformation was observed in the adherends during the experiments. For the Mohr-Coulomb model, a tensile yield stress equal to 28.73 MPa with yield surface modifier equal to 0.001057 was used (Jumbo, [24]). An isotropic hardening behaviour was assumed.

3.2 Progressive damage modelling

The model described in section 2.1 was implemented using an external subroutine written in Python © (Python Software Foundation Inc., Hampton, USA) script with the FEA software. The algorithm used for this purpose is shown in Fig. 7. This can be described in following steps.

Step 1: a finite element model is built and the values for number of cycles, N, and damage, D, are set to zero.

Step 2: a non-linear static analysis is carried out and plastic strain is determined for all the elements in the adhesive layer.

Step 3: check if the analysis converges, if yes then step 4, otherwise $N = N_f$ and stop the program.

Step 4: the damage rate dD/dN is determined for each element in the adhesive using eqn. 1.

Step 5: the new value of damage in each element is calculated using the damage rate calculated in the previous step as:

$$D = D + \frac{dD}{dN} dN \tag{3}$$

where, dN is the increment to number of cycles.

Step 6: check if D=1, if yes then delete the element, and go to step 2.

Step 7: if $D \neq 1$ calculate new material properties as:

$$E = E_0(1 - D) \tag{4}$$

$$\sigma_{yp} = \sigma_{yp0}(1 - D) \tag{5}$$

$$\beta = \beta_0(1 - D) \tag{6}$$

where, E_0, σ_{yp0} and β_0 are Young's modulus, yield stress and plastic surface modifier constant for the parabolic Mohr-Coulomb model respectively.

Step 8: calculate new value of N; go to step 2 and repeat.

The constants m_1 and m_2 were determined by repeating the procedure above for different values at two different fatigue loads and optimising. These constants were then kept constant to determine the life for other fatigue loads. In this way, m_1 and m_2 were used to completely characterise the fatigue damage and failure of the SLJs.

3.3 Evolution of damage and crack propagation

The maximum equivalent plastic strain in the middle of the adhesive layer is plotted across the width of the SLJ in Fig. 8 (a), for a maximum fatigue load of 7.5kN and for zero cycles (i.e undamaged). This load was 63% of the quasi-static failure load (QSFL), which was 11.95 kN, with a standard deviation of 0.31 [8]. It can be seen that the maximum strain occurs in the middle of the joint width, which is at zero on the Z axis because of the symmetric boundary conditions applied during the analysis. The strain is constant in the central region but decreases rapidly at the sample edges. This is consistent with experimental observations that the first cracks always appear in the central region of the SLJ, in the fillet region [8]. In Fig. 8 (b) the plastic strain along the overlap length in the middle of the bondline is shown. It can be seen that the maximum strain is at the end of the overlap region, i.e. below the embedded adherend corner. This is in agreement with the location of first signs of damage and cracking in the joints [8, 17].

Damage progression in an element close to the embedded corner is plotted against number of cycles for different fatigue loads in Fig. 9(b). Similar behaviour was also found in other elements during the simulation. It can be seen that a non-linear increase in damage was found with an acceleration towards the onset of cracking (denoted by D=1). When damage equals unity the element is deleted, hence creating a crack in the adhesive. The damage plot in Fig. 9(b) is for the element E shown in the finite element mesh in Fig. 9(a).

The crack growth (in the central section) for two different fatigue loads is plotted against number of cycles in Fig. 10. Elements were progressively deleted after the first crack formation and varied across the sample width. The crack lengths plotted in this figure are the crack lengths determined at the central section of the adhesive width, however the crack, also travels across the adhesive width during the simulation. This is in agreement with the experimental observations, wherein different lengths of cracks were found at different points across the adhesive. The predicted crack growth calculated is compared with experimental results in the same figure. It can be seen that there is a good match between predicted

and experimental results. The experimental details regarding the measurements of crack lengths can be found in [8, 17].

3.4 Extended S-N curve prediction

The total fatigue life calculated using the UFM matches well with the experimental results as shown in Fig. 11 (a), where, the experimental results are taken from earlier work by the same authors [8, 17]. The total life can be divided into initiation and propagation phases, as explained in section 2.3. It can be seen in Fig. 11 (a) that the predicted proportion of initiation life increases as the fatigue load decreases, as also seen in experiments [17]. The crack propagation life predicted using UFM is compared with that predicted using a fracture mechanics (FM) approach in Fig. 11 (b). More details of the FM approach are given in [20]. It can be seen that there is a difference in the gradient of the predicted propagation life, with the UFM method showing less load dependency, however, the predicted number of cycles spent in propagation to failure agree fairly well.

3.5 Strength and stiffness wearout and BFS prediction

In order to determine the strength degradation, a series of quasi-static loads were applied at each damage increment until the finite element model became unstable. The highest load at which the model converged was taken as an approximate value of the residual failure load of the joint. Stiffness degradation was calculated by applying the maximum fatigue load to the joint and using the deflection of the joint under load to calculate stiffness.

In Fig. 12 strength wearout results are plotted against number of cycles for two different fatigue loads. It can be seen that strength decreases non-linearly with respect to number of cycles with an accelerated strength degradation towards the end of the fatigue life. The predicted values are compared with experimental results taken from [8] in the figure. Excellent agreement between the predicted and

experimental results can be seen. The UFM was also used to predict the stiffness wearout of the SLJs by periodically determining joint displacement throughout the fatigue life. The predicted stiffness wearout is compared with experimental results for a maximum fatigue load of 7.5kN in Fig. 13. Similar to the strength wearout, it can be seen that the stiffness wearout is non-linear with an accelerated degradation towards the end of the fatigue life. There is a reasonable agreement between experimental and predicted strength wearout, however, the experimental results show a sharper decrease. This may be because of a lack of sensitivity in the experimental displacement measurements.

An important method of monitoring fatigue degradation in adhesively bonded joints in-situ is through the measurement of BFS [17, 25-27]. Experimental values of BFS are compared with predicted values in Fig. 14, where experimental values are taken from [17]. Similar values and trends can be seen in the experimental and predicted results. The difference in results can be attributed to the absence of an exact crack propagation scenario in the prediction. In the simulation, symmetric crack growth from both ends of the overlap was assumed, whereas asymmetric crack growth is often observed in practice. A more detailed explanation of these asymmetries is given in earlier work on BFS by the same authors [17].

3.6 Summary

In order to summarise the capabilities of the proposed UFM, the block diagram shown in Fig. 1 is redrawn in Fig. 15, with the results from the constant amplitude fatigue testing of an adhesively bonded SLJ. The hub of the method is the damage propagation law given in eqn. 1. The main input data are the material properties, joint geometry and boundary conditions. Two fatigue life data results were used to determine the constants in damage growth law for the particular joint. These were then used for all other fatigue loads.

Output consists of, firstly, damage evolution and crack propagation predictions as functions of the number of cycles and the fatigue load. Secondly, the extended L-N (or S-N) curve can be plotted, which shows

both initiation and propagation lives as a function of fatigue load. Finally, damage monitoring parameters such as strength wearout, stiffness wearout and BFS can also be determined as functions of the number of fatigue cycles and the fatigue load. Hence, it has been shown that a single damage evolution law can be an effective tool in unifying the prediction of all the important characterisation of fatigue in bonded joints.

6. Conclusions

It has been shown that a damage progression law governed by equivalent plastic strain can be used as a unified method to predict all the major parameters associated with fatigue in bonded joints. Output from the method includes, BFS, strength and stiffness wearout, 3D damage evolution and crack propagation maps and fatigue initiation and propagation lives. The technique is versatile and potentially can be used to also predict variable amplitude fatigue and combined creep fatigue with little further adaptation.

7. References

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Figure(s)

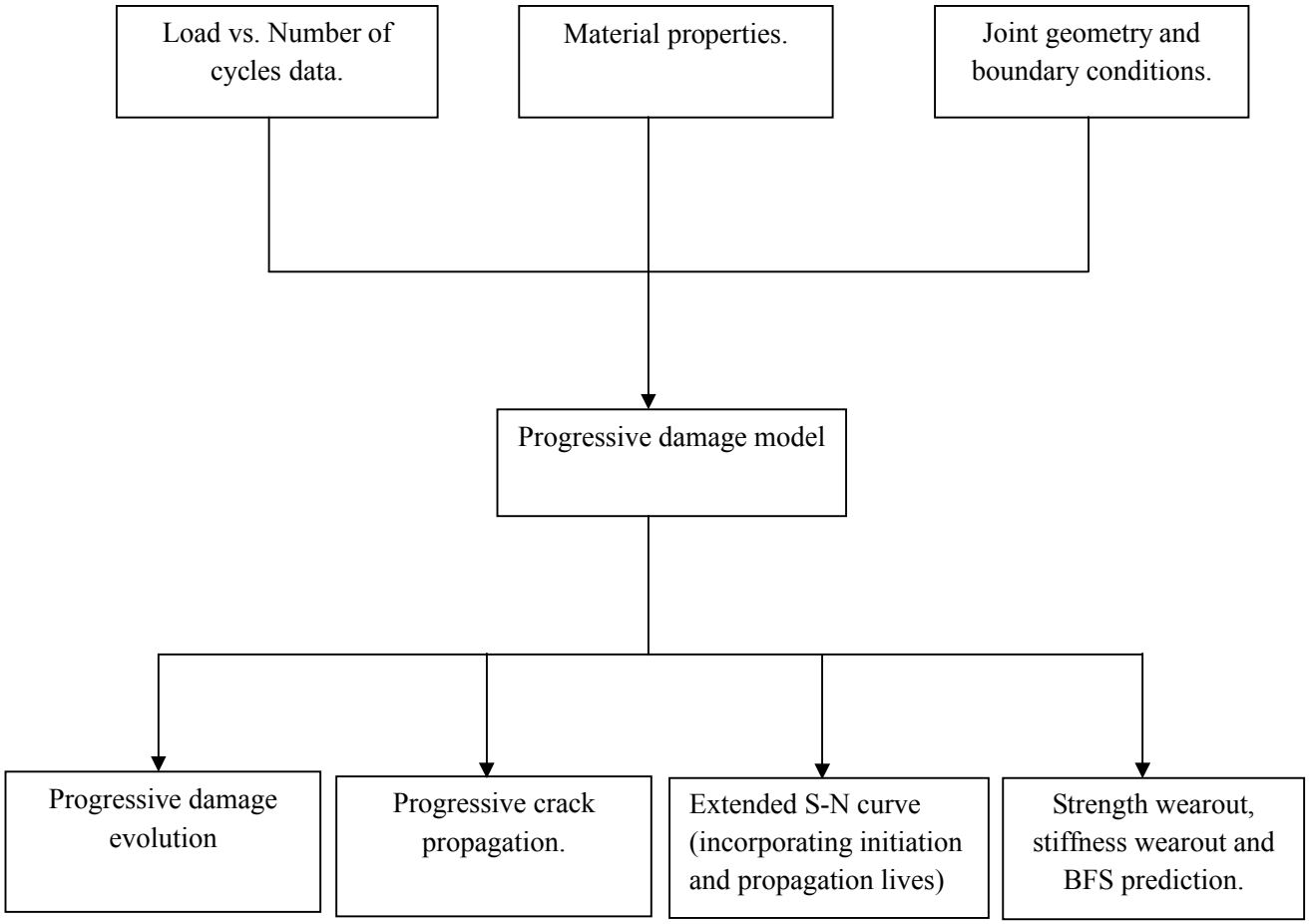


Fig. 1. Schematic representation of Unified Fatigue Methodology.

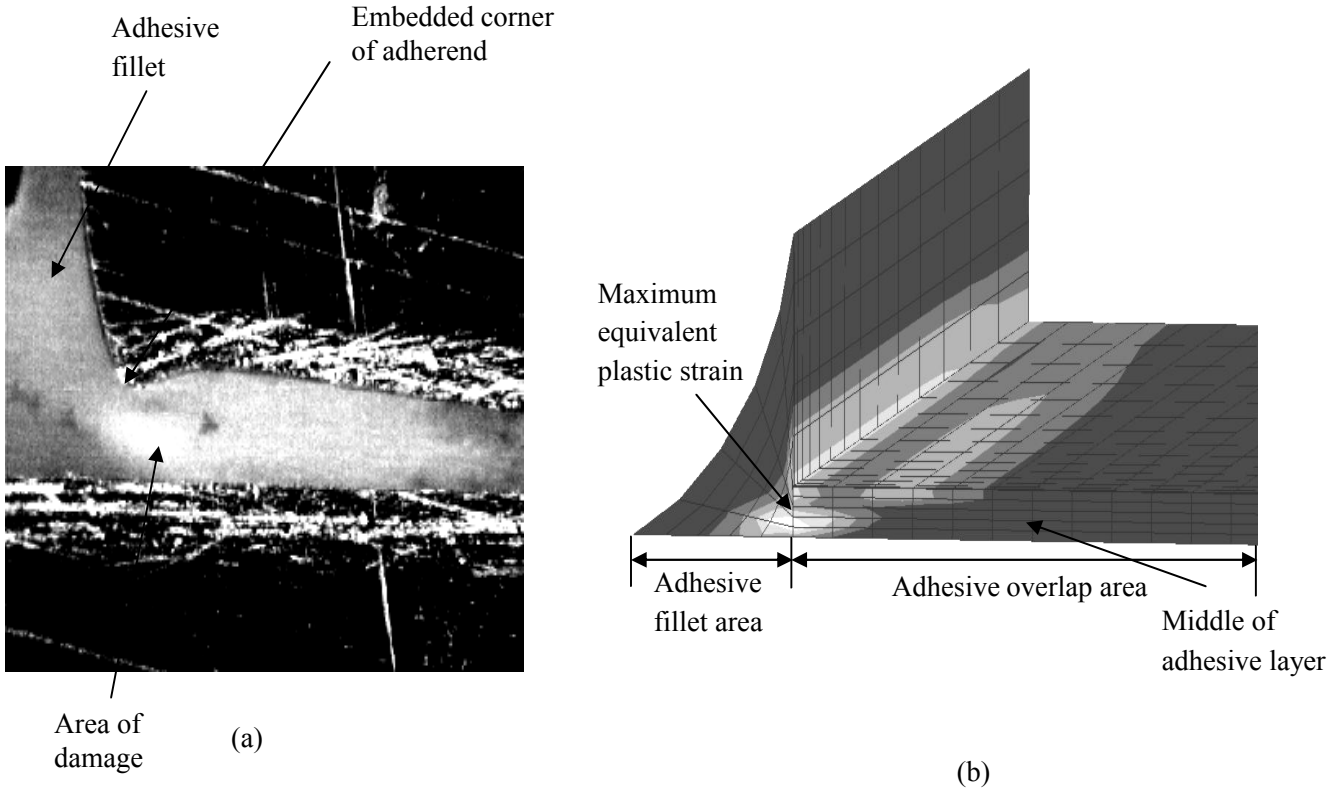


Fig. 2. Comparison between (a) damaged region observed in polished cross section and (b) the location of maximum equivalent plastic strain shown in finite element mesh of adhesive layer.

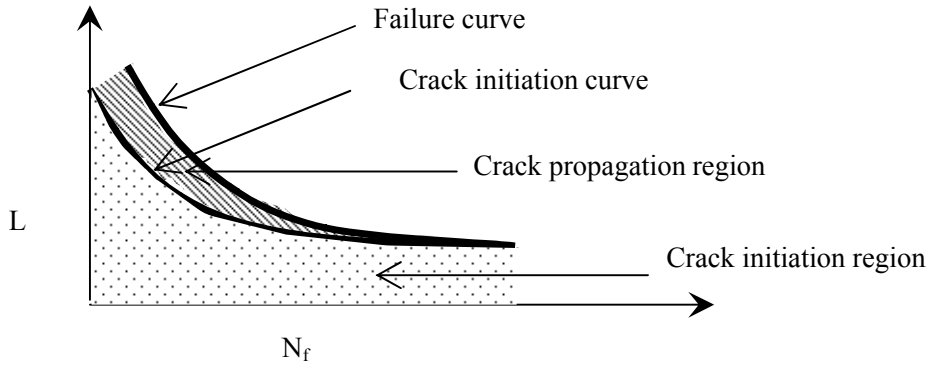


Fig. 3. Schematic representation of extended L-N diagram.

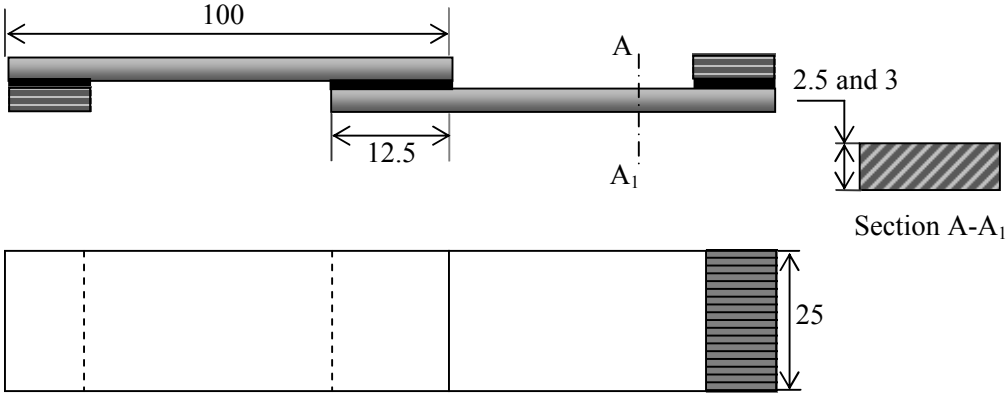


Fig.4. Single lap joint (dimensions in mm).

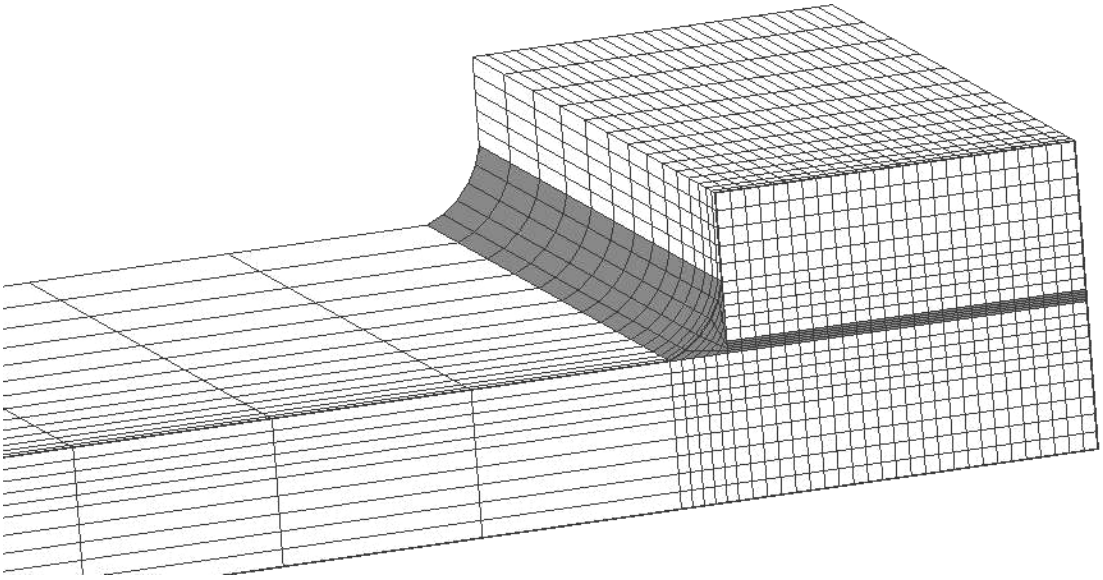


Fig. 5. Typical mesh used for 3D crack propagation.

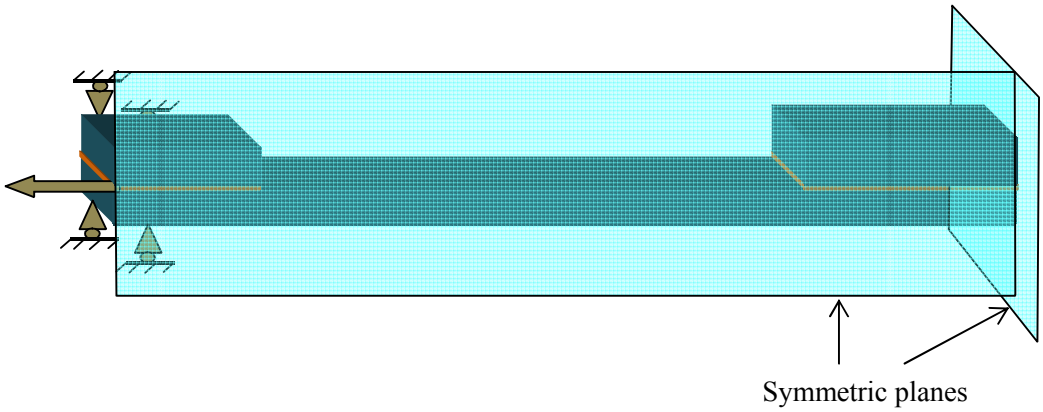


Fig. 6. Schematic sketch showing boundary conditions used for the analysis

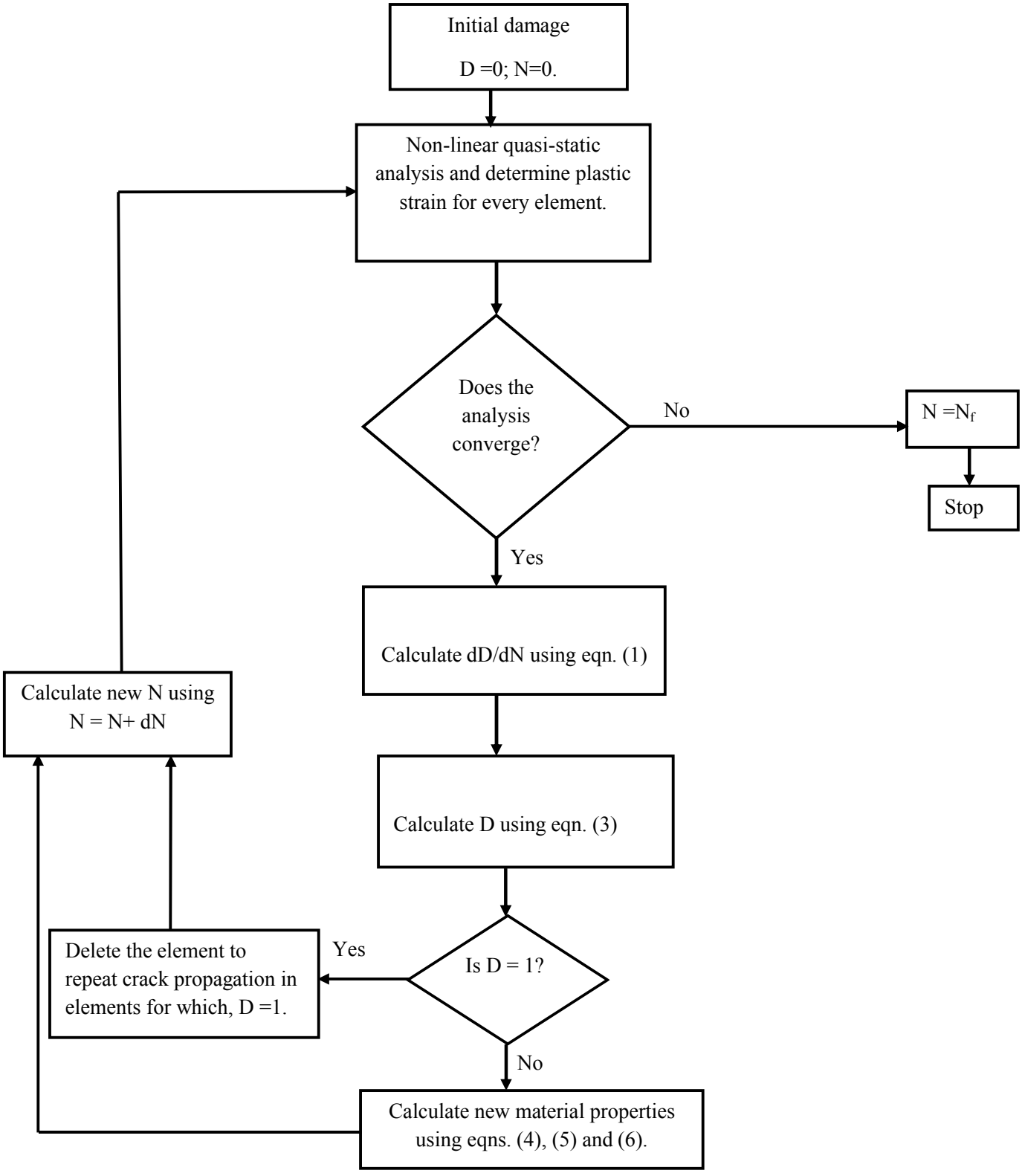


Fig. 7. Algorithm for DM based fatigue prediction.

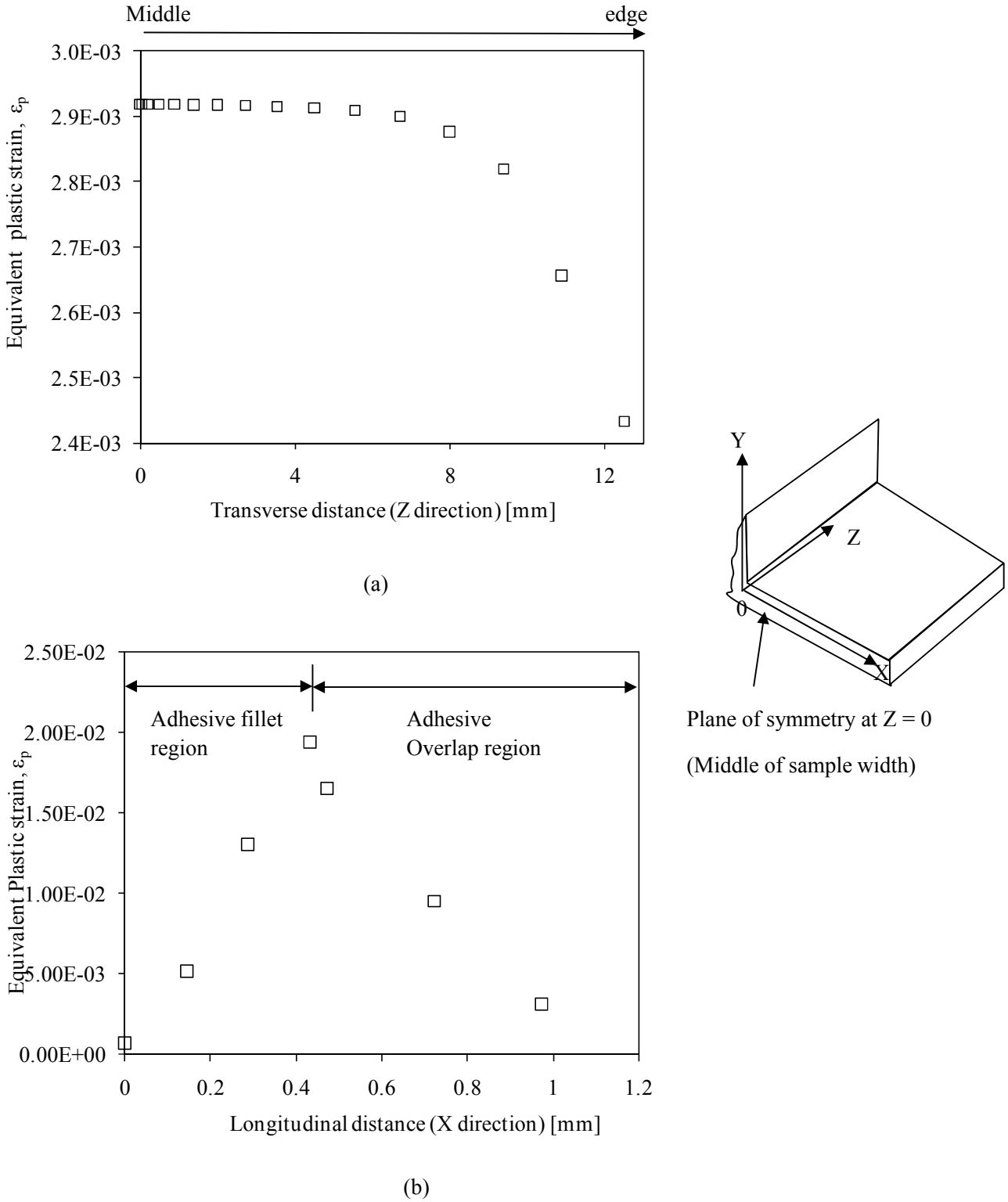
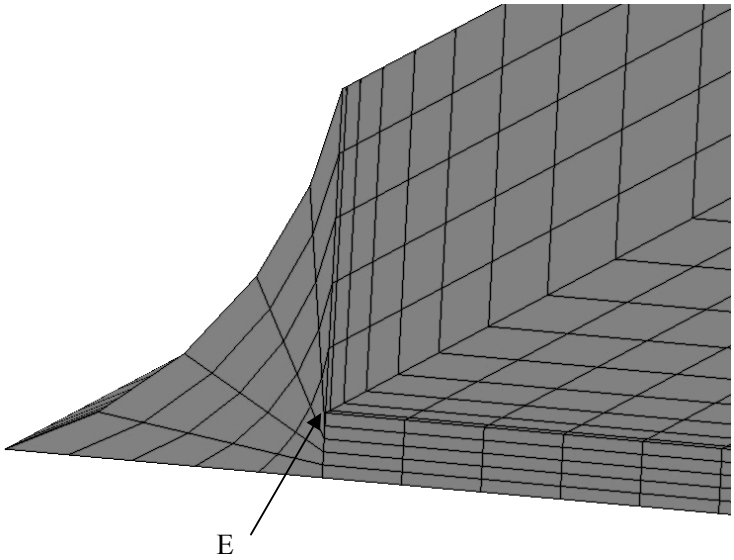
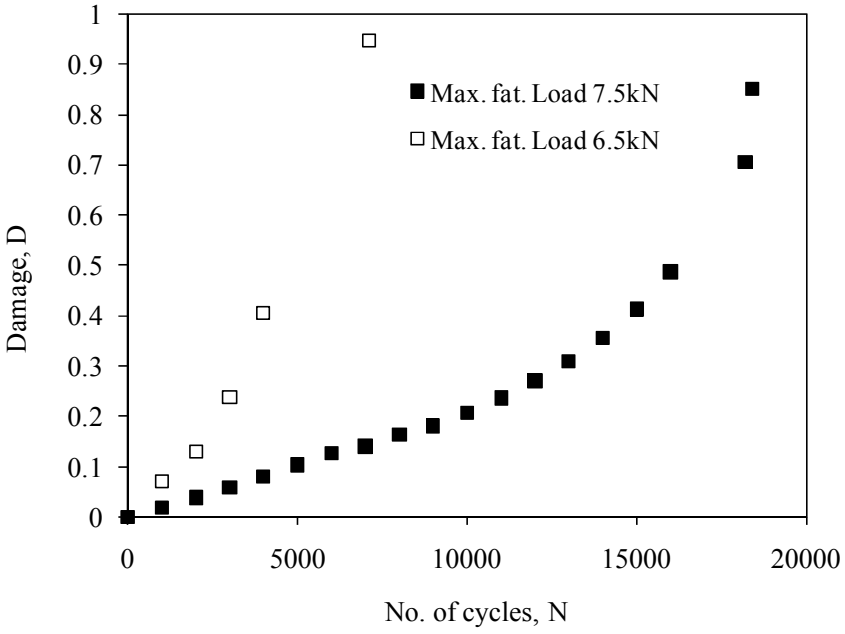


Fig.8. Equivalent plastic strain distribution plotted (a) along the adhesive glue line and (b) across the width for the SLJ.



(a)



(b)

Fig.9. (a) Element E, in the embedded corner region, (b) Damage in element E prior to initial crack as a function of cycles for different fatigue loads.

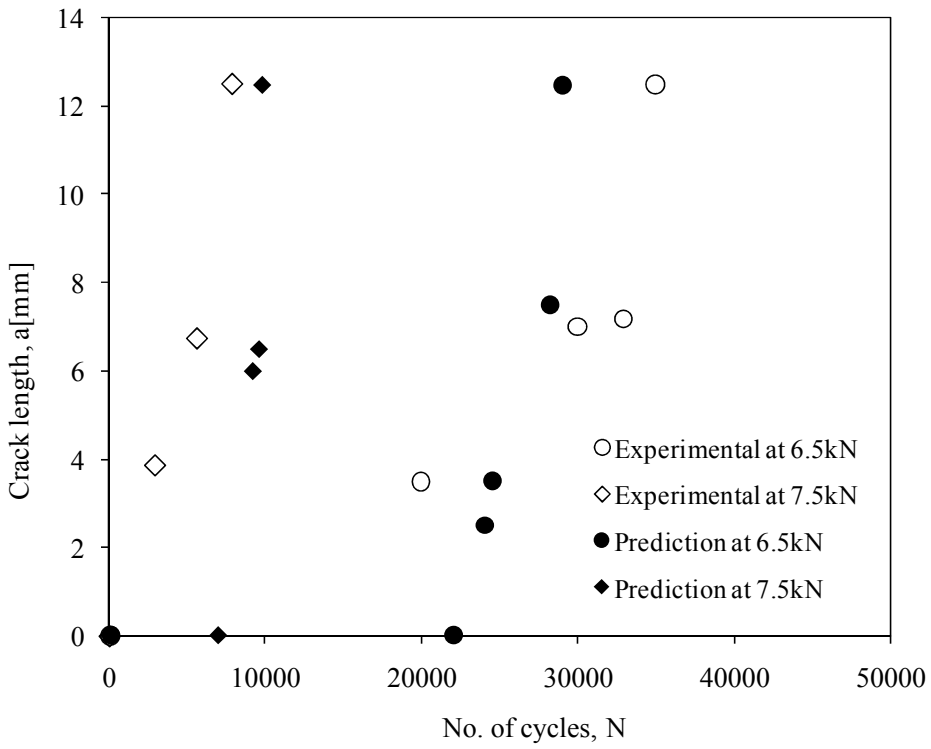
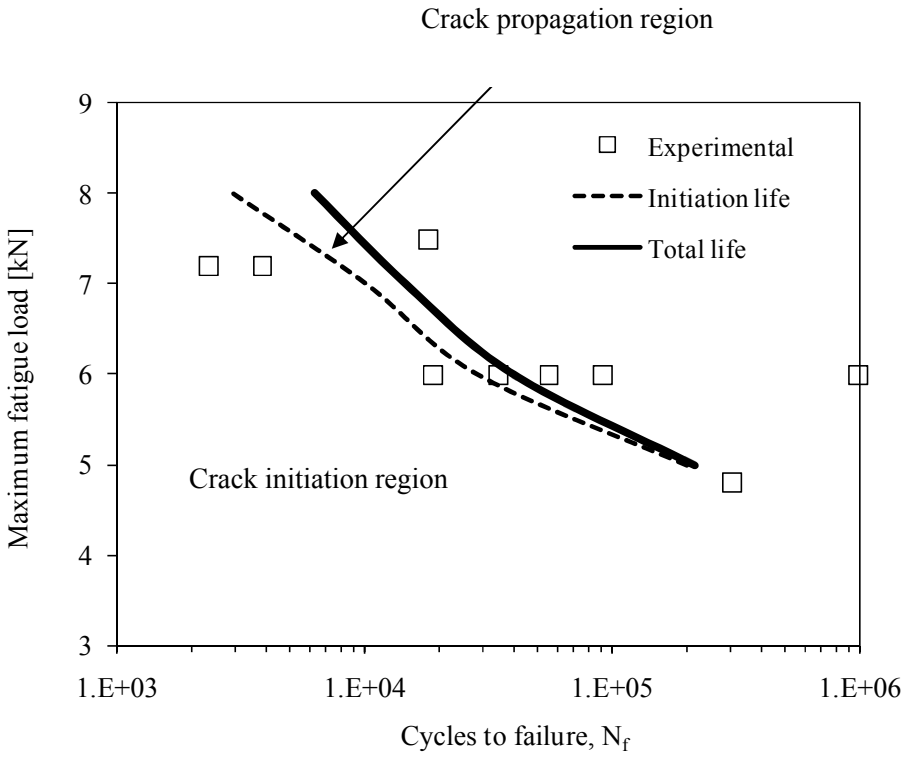
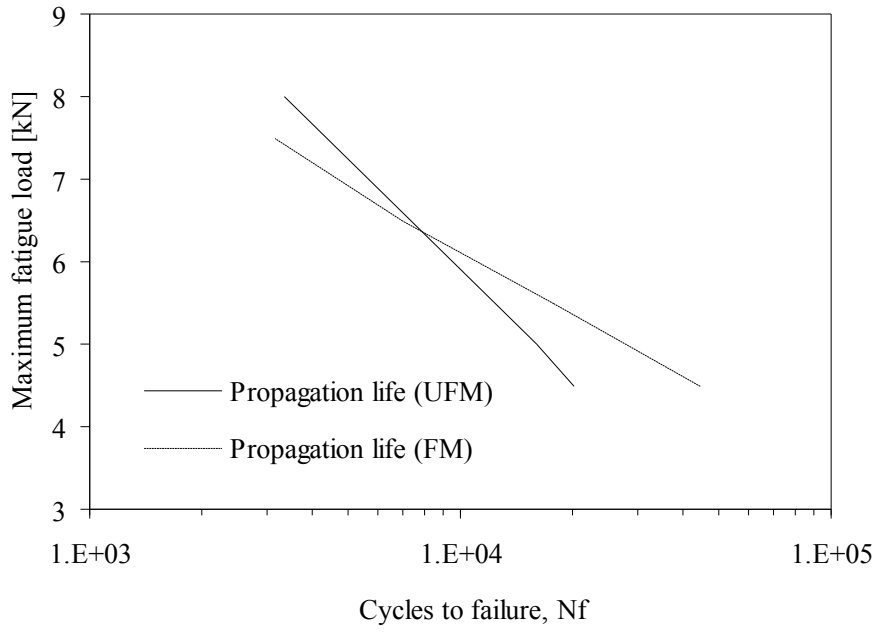


Fig.10. Comparison of crack growth prediction with experimental crack growth for different fatigue loads.



(a)



(b)

Fig.11. (a) extended L-N curve using UFM and (b) comparison between FM and UFM for propagation lives.

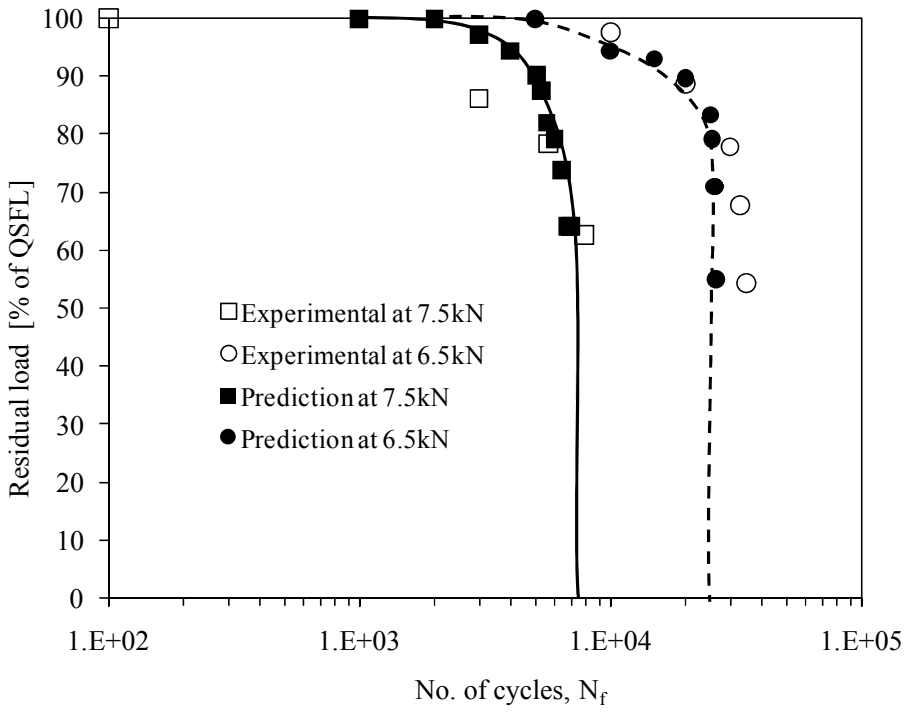


Fig. 12. Comparison between experimental and predicted strength wearout for different maximum fatigue loads.

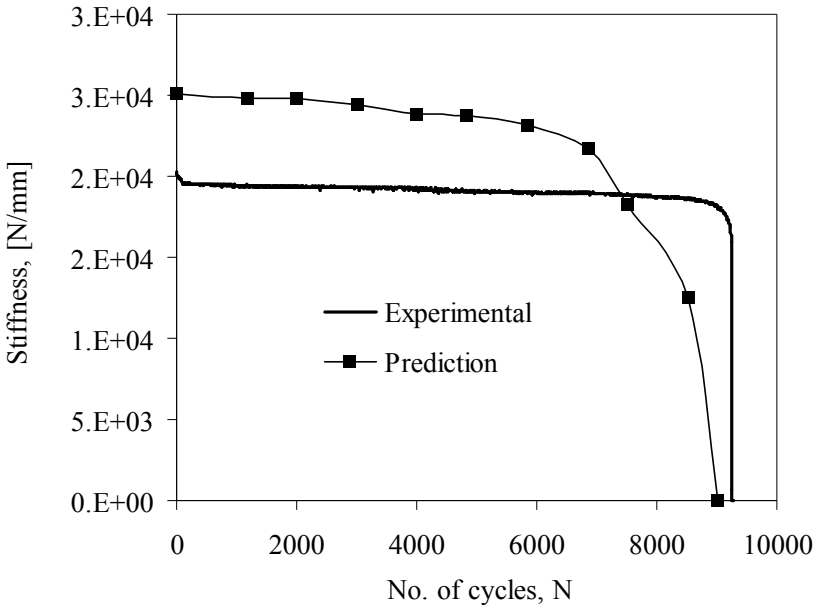


Fig. 13. Comparison between experimental and predicted stiffness wearout for maximum fatigue load equal to 7.5kN.

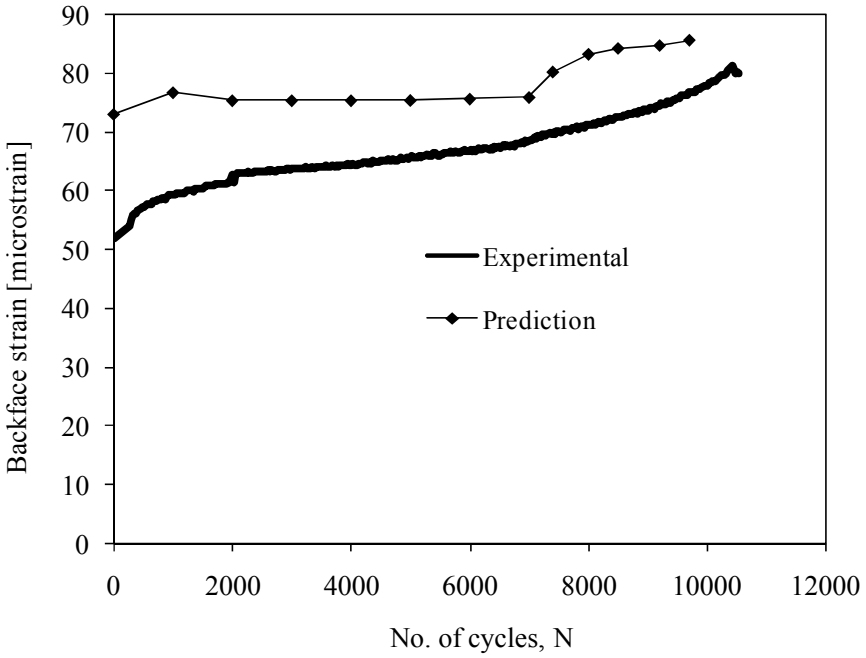


Fig. 14. Comparison between experimental and predicted BFS for maximum fatigue load equal to 7.5kN.

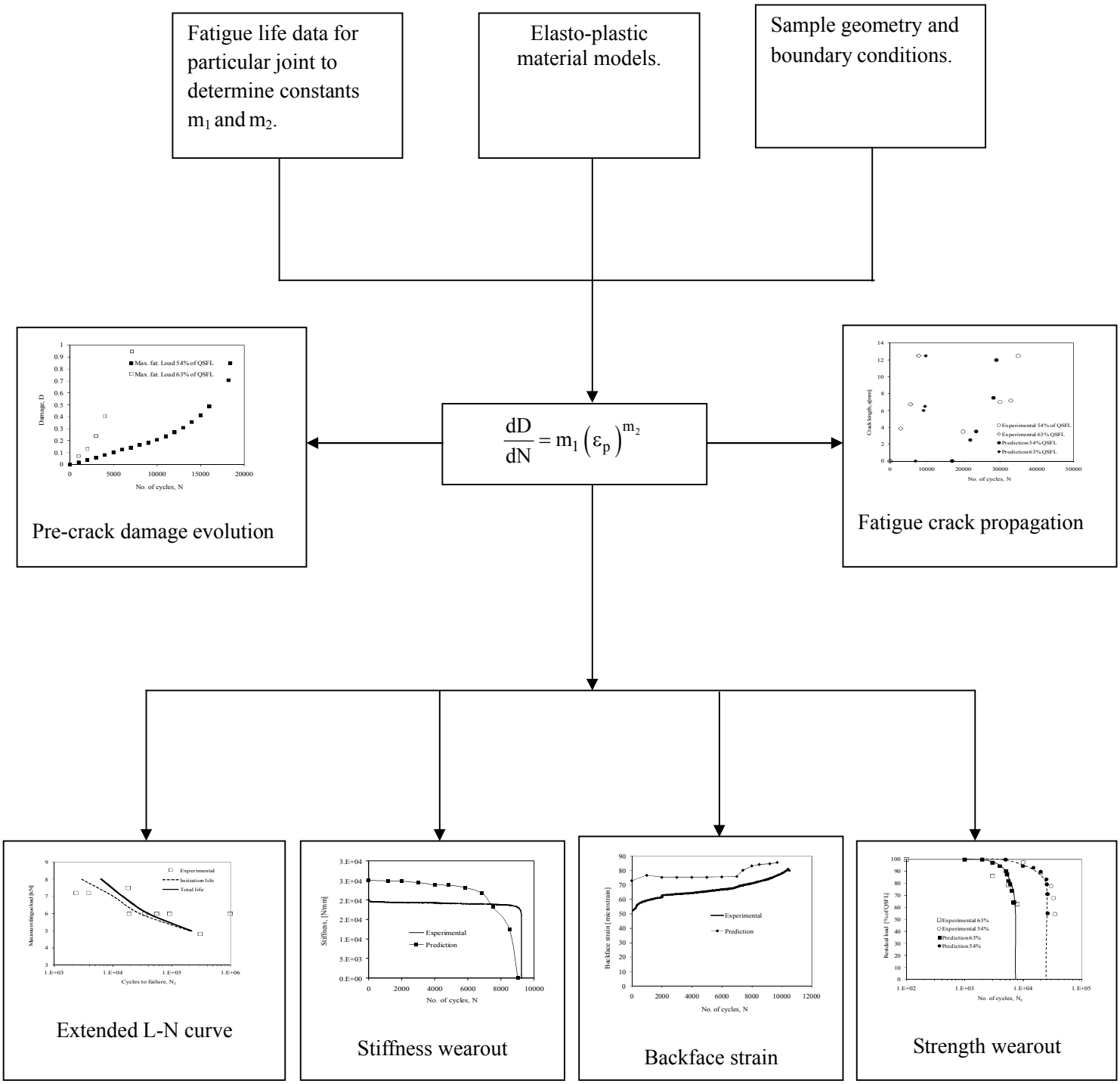


Fig. 15. UFM summarised with inputs and outputs for SLJ under constant amplitude fatigue loading.