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NUMERICAL ANALYSIS OF THE DAMAGE EVOLUTION IN A COMPOSITE PIPE JOINT UNDER CYCLIC STATIC AXIAL TENSION

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The main goal of this paper is to present a computational analysis of damage evolution in adhesive joint connecting composite pipes subjected to cyclic static axial tension with constant amplitude. The approach uses the simplified average shear stress criterion for defect propagation in the adhesive layer and applies the continuum damage mechanics concept to continuum crack-like damage representation in terms of the finite element stiffness. Numerical studies are performed using the commercial Finite Element Method displacement-based ANSYS program, with its special purpose finite element containing birth and death option. Computed damage evolution per a loading cycle leads further to estimation of the cumulative damage growth in terms of a crack-like type for different load amplitude levels. Finally, a numerically determined relation between the applied load amplitude and the load cycles number to failure is derived.

Key words: fatigue life prediction, Finite Element Method, composite pipe, adhesive joint, structural damage evolution.

1. Introduction

For many years composite materials have been extensively used in piping systems as an efficient alternative to carbon and stainless steel structures, in corrosive fluid transport and in the petrochemical as well as in pulp industries. Nowadays, composite pipe acquires its importance in the offshore oil and gas industry due to its light weight and corrosion resistance. Limitations on composite pipes sizes resulting from manufacturing and transport, inspection and repair requirements, make the application of composite pipe joints inevitable in all piping systems. The continued integrity and long-term durability of new composite pipelines depend partially on the integrity of the adhesive bonds for joining the pipe sections, as it was reported in [1]. Composite pipes used in marine and oil industry applications exhibit the adhesive joints as the weakest link in a composite piping system, as it is reported in [2]. Thus, in order to increase the reliability of adhesive bonded joints, more detailed theoretical, experimental and computational studies of these joints are necessary. Pipe joints are usually subjected to internal liquid pressure, and/or external thermomechanical loadings – axial or bending loads arising from expansion, contraction and pressure variations in real engineering pipeline systems.

That is why the issue of fatigue crack-like damage propagation in a composite pipe joint under axial tension is computationally studied in this paper. The averaged shear stress criterion for damage propagation in the adhesive layer is used. The concept of the continuum crack-like damage is represented in terms of the finite element stiffness [3] as a damage measure [4]. The crack-like damage propagation in the adhesive layer is analysed as a function of load cycles and load amplitude in numerical studies performed by means of the Finite Element Method (FEM) displacement-based program ANSYS [5]. The numerical approach presented makes it possible to predict composite pipe joint life under axial loads only and to propose a relation between amplitude of the applied load *versus* the number of cycles to failure. Next, this problem can be extended to numerical analysis of damage evolution under random material parameters and implemented in the framework of the Probabilistic Design System of ANSYS.

2. Computational damage model

2.1. *Simplified damage model of a composite pipe joint*

Deterministic computational model of a crack-like damage propagation within a composite pipe joint is based on the following assumptions:

- composite components are linear elastic and transversely isotropic materials;
- three-dimensional problem is simplified to the axisymmetric case with four components of the stress tensor $\boldsymbol{\sigma}=\{\sigma_A, \sigma_R, \sigma_H, \tau_{RA}\}$;
- neither bending nor large deformation effects are included;
- possible defect nucleation and growth is localized in the adhesive layer and results from the high stress concentrations at the joint edges;

- no initial manufacturing flaws, pre-cracks or other defects are assumed to exist in the original adhesive layer (before the beginning of the static cyclic loading process);
- there are no microdefects forming and their coalescence during composite tension (typical for metallic materials) apart from crack formation and propagation;
- the static cyclic load has constant amplitude in time;
- no time-dependent nonlinear effects such as creep due to the static cyclic loading character are considered;
- fatigue crack-like damage propagation is stable.

Further, it is known that the stresses along the adhesive layer are not uniform and their gradients arise at the joint edges. It results from extension of the specimen layers in the opposite directions (composite pipe and coupling), cf. Fig. 1. Then it is assumed that the defect starts to grow longitudinally along the adhesive layer, uniformly over all the pipe circumference under tensile load, when the resulting average shear stress $\langle \tau_{RA(ad)} \rangle$ over some distance d on the high stress concentration region satisfies the following relation:

$$\langle \tau_{RA(ad)} \rangle = \frac{1}{d} \int_0^d \tau_{RA(ad)} \, dX_A \geq \tau^u_{RA(ad)}, \tag{2.1}$$

where $\tau^u_{RA(ad)}$ denotes the static shear strength of the adhesive layer.

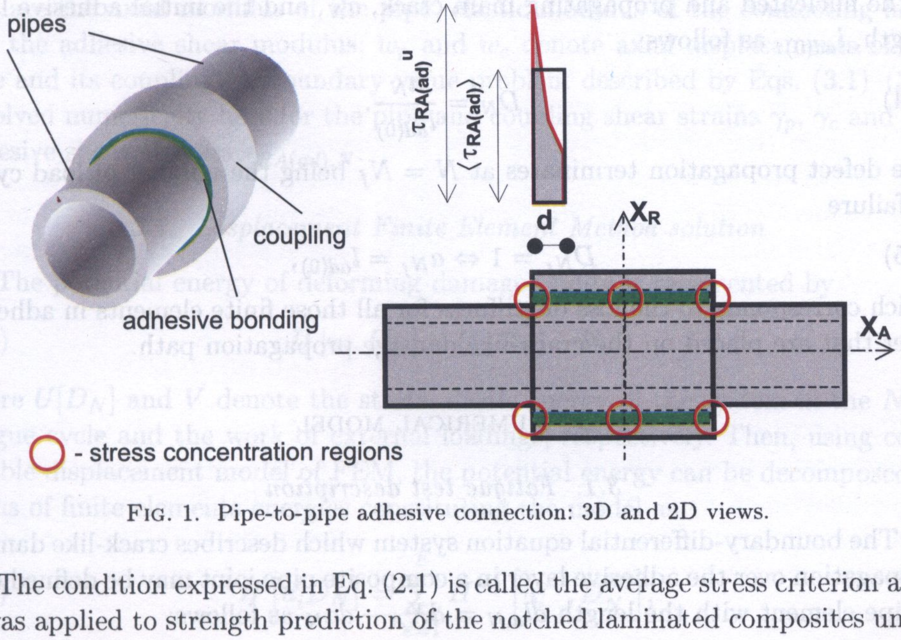

FIG. 1. Pipe-to-pipe adhesive connection: 3D and 2D views.

The condition expressed in Eq. (2.1) is called the average stress criterion after it was applied to strength prediction of the notched laminated composites under uniaxial tension [6]; graphical representation of this criterion is schematically shown in Fig. 1. The distance d is called the characteristic length and can stand for the damage accumulated or nonlinear process zone. Here it is expressed in terms of the critical fracture mechanics parameter as the critical Stress Intensity Factor (K_{IIc}) and shear strength of the adhesive layer as

$$d = \frac{1}{2\pi}\left(\frac{K_{IIc}}{\tau^{u}_{RA(ad)}}\right)^{2}. \tag{2.2}$$

Since Eq. (2.2) is based on the assumption of the square-root stress singularity at the front of the sharp crack tip, it does not represent precisely the stress distribution in the tubular adhesive layer in the stress concentration region or when the crack-like damage zone is present. However, this characteristic length serves only to estimate the upper bound on the finite element size at the crack-like damage tip.

Therefore, it is postulated that after the crack-like defect has nucleated, it steadily propagates along the adhesive layer as the main single crack-like damage zone and leads to average shear stress increase over the distance d together with the number of load cycles N as

$$\langle \tau_{RA(ad),N} \rangle = \frac{1}{d}\int_{0}^{d} \tau_{RA(ad),N}\, dX_A \Rightarrow \frac{1}{d}\int_{0}^{d} \frac{\tau_{RA(ad),N}}{1 - D_N}\, dX_A. \tag{2.3}$$

D_N denotes the classical scalar damage variable which may be written in terms of the nucleated and propagating main crack, a_N, and the initial adhesive layer length, $l_{ad(0)}$, as follows:

$$D_N = \frac{a_N}{l_{ad(0)}}. \tag{2.4}$$

The defect propagation terminates at $N = N_f$ being the number of load cycles at failure

$$D_{N_f} = 1 \Leftrightarrow a_{N_f} = l_{ad(0)}, \tag{2.5}$$

which corresponds to the loss of stiffness for all those finite elements in adhesive layer that are placed on the crack-like damage propagation path.

3. Numerical model

3.1. *Fatigue test description*

The boundary-differential equation system which describes crack-like damage propagation over the adhesive layer in a composite pipe joint may be defined over a pipe element with the length $dl_{a,N} = dX_A - da_N$ as follows:

(i) equilibrium and damage equations

$$dF_p = dF_{ad,N} = dF_c, \tag{3.1}$$

$$d\sigma_p \frac{\pi}{4}\left(D_{op}^2 - D_{ip}^2\right) = \tau_{RA(ad),N}\pi D_{op} dl_{a,N}, \tag{3.2}$$

$$d\sigma_c \frac{\pi}{4}\left(D_{oc}^2 - D_{ic}^2\right) = \tau_{RA(ad),N}\pi D_{ic} dl_{a,N}; \tag{3.3}$$

(ii) constitutive relations

$$\frac{dw_p}{dl_N} = \frac{\sigma_A}{E_p} \quad \text{and} \quad \frac{dw_c}{dl_N} = \frac{\sigma_A}{E_c}, \tag{3.4}$$

$$\tau_{RA(ad),N} = \frac{G_{RA(ad)}\left(\gamma_p - \gamma_c\right)}{t_{ad}}; \tag{3.5}$$

(iii) boundary conditions

$$\left.\frac{dw_p}{dl_N}\right|_{X_A=l_p} = \frac{\sigma^{\mathrm{app}}}{E_p} \quad \text{and} \quad \left.\frac{dw_c}{dl_N}\right|_{X_A=0} = \frac{\sigma^{\mathrm{app}}}{E_c}, \tag{3.6}$$

$$\left.\frac{dw_p}{dl_N}\right|_{X_A=0} = 0 \quad \text{and} \quad \left.\frac{dw_c}{dl_N}\right|_{X_A=l_p} = 0, \tag{3.7}$$

where $F_{p,N}$, $F_{ad,N}$, $F_{c,N}$ represent internal axial forces in the pipe, adhesive layer and coupling, respectively; internal axial stresses in the pipe, adhesive and coupling are denoted by σ_p, $\tau_{RA(ad),N}$ and σ_c. Let us assume that E_p, E_c and G_{ad} are the axial modulus of the pipe, elastic modulus of the connecting layer and the adhesive shear modulus; w_p and w_c denote axial displacements of the pipe and its coupling. A boundary value problem described by Eqs. (3.1)–(3.7) is solved numerically here for the pipe and coupling shear strains γ_p, γ_c and the adhesive shear stresses $\tau_{RA(ad),N}$.

3.2. *Displacement Finite Element Method solution*

The potential energy of deforming damaged body is represented by

$$\Pi\left[u_i, D_N\right] = U\left[D_N\right] - V, \tag{3.8}$$

where $U[D_N]$ and V denote the strain elastic energy of the system in the N-th fatigue cycle and the work of external loadings, respectively. Then, using compatible displacement model of FEM, the potential energy can be decomposed in terms of finite elements energies constituting the model as

$$\Pi\left[u_i' D_N\right] = \sum_{e=1}^{E} \Pi^{(e)}\left[u_i^{(e)}, D_N^{(e)}\right], \tag{3.9}$$

where E denotes the total number of finite elements in the model and the index e refers to the e-th finite element; $u_i^{(e)}$ represents the vector of discretized displacements. Then, it is assumed that the functions $u_i(x_k)$ for $x_k \in \Omega_e$ are approximated in each e-th finite element by the shape functions $\varphi_{i\xi}^{(e)}(x_k)$ as simply $u_i^{(e)}(x_k) = \varphi_{i\xi}^{(e)}(x_k) q_\xi^{(e)}$ [3] with $\xi = 1, 2, \ldots, N^{(e)}$. The vector of element nodal displacements is represented by $q_\xi^{(e)}$ with $N^{(e)}$ denoting the number of degrees of freedom in this element. As far as linear elastic material behavior is assumed, the total potential energy of the system can be defined as

$$\Pi\left[u_i, \Phi\right] = \sum_{e=1}^{E} \left[\int_{\Omega_e} \frac{1}{2} \varepsilon_{ij}^{(e)T} C_{ijkl}^{(e)} \left(D_N^{(e)}\right) \varepsilon_{kl}^{(e)} d\Omega - \int_{\Omega_\sigma} t_i^T u_i d(\partial\Omega) \right]. \tag{3.10}$$

Finally, as a result of the first variation of the potential energy functional with respect to particular nodal displacement component $(\partial\Pi/\partial q_\alpha)$, it is possible to obtain the basic FEM system of algebraic equations to be solved for the unknown nodal displacements as

$$\sum_{e=1}^{E} \left\{ k_{\alpha\beta,N}^{(e)} q_{\beta,N}^{(e)} \right\} = \sum_{e=1}^{E} f_\alpha^{(e)} \quad \text{(no summation over } N\text{)}, \tag{3.11}$$

$$k_{\alpha\beta,N}^{(e)} = \begin{cases} k_{\alpha\beta(0)}^{(e)} & \Rightarrow \text{ no damage,} \\ r^{(e)} \times k_{\alpha\beta(0)}^{(e)} & \Rightarrow \text{ damage} \end{cases} \tag{3.12}$$

where two values are assigned to the damage variable only: $r^{(e)}=1$ or $r^{(e)}=1\times 10^{-6}$, and that is why the element stiffness is equal to its initial value or 0. It is observed that no energy is dissipated due to the propagating crack-like damage according to the Griffith model [8] and the damage propagation is considered only as the material volume reduction by the corresponding reduction of the finite element stiffness. The Stochastic Finite Element Method (SFEM) or the Monte-Carlo simulation (MCS) can be used in case of some input parameters of the analysis being random variables or fields [7].

4. Computational illustration and discussion

The purpose of this computational study is two-fold: (1) life prediction of the composite pipe joint subjected to the pure tension static cyclic load and (2) estimation of load amplitude level on the joint life. The composite pipes joint degradation is described by the relation between crack-like damage length *versus* fatigue load cycles number. Computational experiments are arranged as follows:

- determination of the crack-like damage growth per cycle;
- calculation of the cumulative crack-like damage growth *versus* the loading cycles number;
- estimation of the relation between the load amplitude level and the loading cycles number to failure.

The load applied varies with time as it is shown in Fig. 2 and each load cycle is divided into two time intervals of 6 months. The cycle asymmetry ratio R is equal to 0, while the load amplitude is equal to the applied maximum load, $\sigma_{\max}$. Since static cycle load is applied, no frequency effect is considered here.

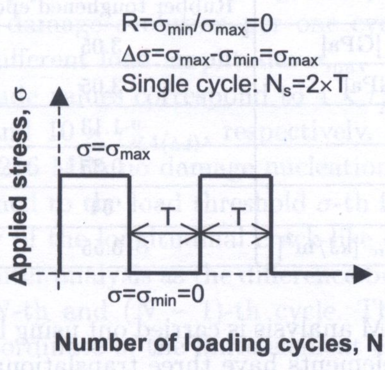

FIG. 2. Applied fatigue load.

Let us note that the axial symmetry of the composite pipe joint results in a simplification of the entire computational model and essentially speeds up the numerical analysis – only one half of the composite pipe joint in axial direction

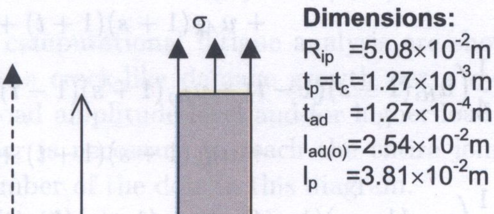

FIG. 3. Computational model.

is considered due to its symmetry. The final computational model geometrical input to the FEM displacement-based commercial program ANSYS is schematically shown in Fig. 3. The pipe and the coupling component are made up of a unidirectional E-glass-reinforced epoxy composite (50% fiber volume fraction) with material properties taken from [9], and adhesive layer (rubber-toughened epoxy) properties are used [10]. All material properties of the composite pipe joint components are listed in Table 1.

Table 1. Material properties of the model.

Property	Rubber toughened epoxy	E-glass/epoxy
Longitudinal modulus [GPa]	3.05	45
Transverse modulus [GPa]	3.05	12
Shear modulus [GPa]	1.13	5.5
Poisson's ratio	0.35	0.28
Shear strength [MPa]	54	70
Fracture toughness G_{Iic} [kJ/m^2]	3.55	–

The axisymmetric FEM analysis is carried out using four node finite elements PLANE42. These finite elements have three translational nodal degrees of freedom (DOF) in the axial $u_{A(i,j,k,l)}$, radial $u_{R(i,j,k,l)}$ and hoop $u_{H(i,j,k,l)}$ directions. Then, the finite element displacements are described using the following linear functions:

$$(4.1)\qquad u_A = \frac{1}{4}\Big(u_{Ai}(1-s)(1-t) + u_{Aj}(1+s)(1-t) + u_{Ak}(1+s)(1+t) + u_{Al}(1-s)(1+t)\Big),$$

$$(4.2)\qquad u_R = \frac{1}{4}\Big(u_{Ri}(1-s)(1-t) + u_{Rj}(1+s)(1-t) + u_{Rk}(1+s)(1+t) + u_{Rl}(1-s)(1+t)\Big),$$

$$(4.3)\qquad u_H = \frac{1}{4}\Big(u_{Hi}(1-s)(1-t) + u_{Hj}(1+s)(1-t) + u_{Hk}(1+s)(1+t) + u_{Hl}(1-s)(1+t)\Big).$$

The model mesh is prepared to have greater density in high stress concentration regions – at the top (t) and the bottom edge (b) of the joint. In these regions the finite element size was equal to the process zone 'd' calculated from Eq. (2.2). During solution, the averaged value of shear stress component computed in the finite element was compared to the static shear strength ($\tau^u_{RA(ad)}$) of the adhesive layer.

Once this value has been exceeded in some element, its stiffness is multiplied by the reduction factor equal to $r^{(e)} = 1 \times 10^{-6}$ and element is deactivated. This analysis was terminated when all the finite elements in adhesive layer placed on the crack-like damage propagation path had been deactivated (a lack of material along the crack path). The frontal equation solver was used together with the Newton–Raphson iteration technique for the problem solution.

For the purpose of simplification of this analysis, it was assumed that the only active failure mode is the bonding failure. However, it is necessary to mention that it is only one of several failure modes occurring in the composite pipes joint, i.e. tensile failure in the pipe or in the coupling, as reported in [11].

First, the crack-like damage evolution per one cycle in the adhesive layer was computed for five different load amplitudes $\sigma_{\max} = 216$, 243, 270, 406 and 540 MPa. These amplitude values correspond to $4 \times \tau^u_{RA(ad)}$, $4.5 \times \tau^u_{RA(ad)}$, $5 \times \tau^u_{RA(ad)}$, $7.5 \times \tau^u_{RA(ad)}$ and $10 \times \tau^u_{RA(ad)}$, respectively. Since below the applied load amplitude $\sigma_{\max} = 216$ MPa no damage nucleation was observed, thus this load value may be assigned to the load threshold σ-th for the crack-like damage evolution. The tendency of the longitudinal crack-like damage propagation was obtained from the computer analysis as the difference between crack-like damage tip $X_{A(N,N-1)}$ at the N-th and $(N-1)$-th cycle. The crack-like damage tip position was an axial coordinate of the finite element centroid with the reduced stiffness with respect to the global coordinate system origin. Since the crack-like damage growth occurred from two opposite sides of the joint, therefore two extreme longitudinal positions of the crack-like damage tips were considered, namely t and b. Thus, the total crack-like damage growth per cycle is described as

$$\Delta a_N = X^{t,b}_{A(N)} - X^{t,b}_{A(N-1)}. \tag{4.4}$$

The main results of computational fatigue analysis are shown in Fig. 4. As it could be expected, the crack-like damage growth per a cycle increases along with the increasing load amplitude level and for higher load amplitude, smaller loading cycles number is necessary to reach the entire joint failure; it is well illustrated by the number of the dots in this diagram.

The results of crack-like damage growth per a cycle were summed separately for each load amplitude level, to establish a single crack-like damage value as

$$a_N = a^{t,b}_{N-1} + \Delta a^{t,b}_N. \tag{4.5}$$

The values of a cumulative crack-like damage growth *versus* number of the loading cycles for different amplitudes are shown in Fig. 5. The loading cycles number N was smaller or equal to the entire joint failure $N = N_f$ denoted by dots. As it was expected, the loading cycles number at the total failure increases together with decreasing load amplitude level.

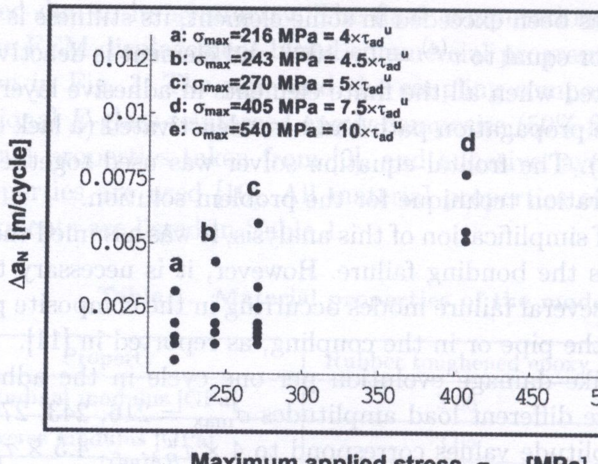

FIG. 4. Crack-like damage growth per cycle.

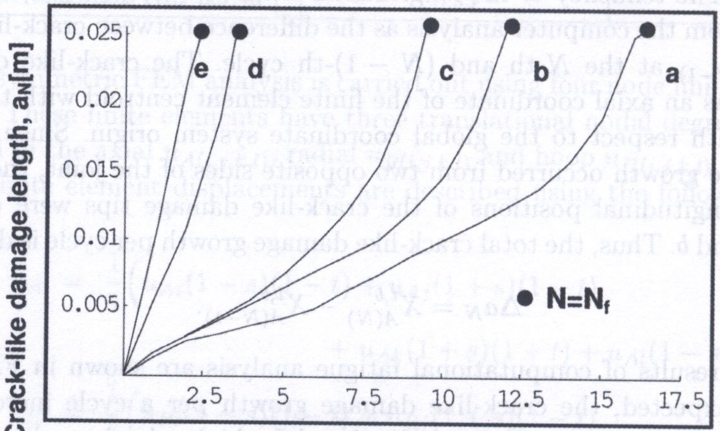

FIG. 5. Cumulative crack-like damage growth.

Finally, it was possible to obtain a relation between the load amplitude level $\sigma_{\max}$ and the loading cycles number at joint failure N_f. This relation is obtained by linear extrapolation of the results in natural logarithmic scale, which is presented in Fig. 6. The following relation for prediction of the number of loading cycles at the joint failure was proposed:

$$N_f = 1.856 \times 10^6 \times \frac{1}{\sigma_{\max}^{2.174}}. \tag{4.6}$$

It is believed that the usage of Eq. (4.6) enables to predict the composite pipe joint life by specification of the load amplitude level only. However, it should be compared with other computational approaches to this problem and the relevant experimental results. For the material system with different material properties, it would be necessary to repeat all numerical procedures carried out here since α and β are material-dependent parameters.

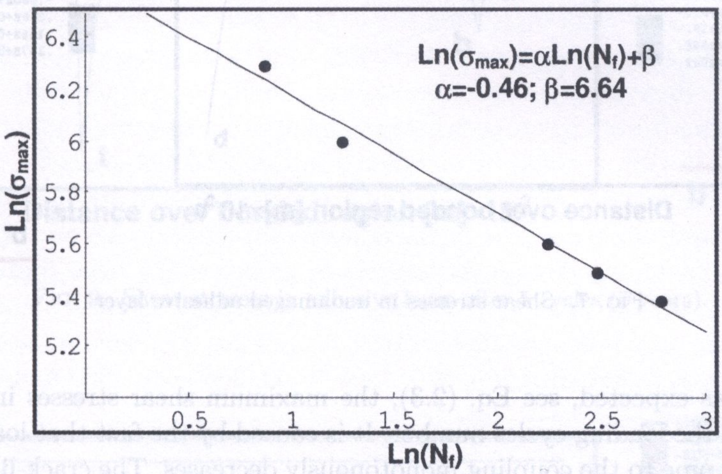

FIG. 6. Fatigue life-prediction line.

The predicted life of composite pipe joint is relatively short, as one could expect to be realistic. In fact, the pipelines are usually designed for about 40 to 50 years of the reliable performance. Short life of the composite pipe joint, as determined in this study, is probably a consequence of several assumptions of the computational model. Certainly, introducing of material nonlinearity, such as creep effects, might elongate the computed life of composite pipe, joint. Furthermore, it is necessary to mention that composite pipe, as well as the coupling, usually consist of layers with the reinforcement located at various angles during manufacturing. An effect of layers orientation is an important aspect in determination of the fatigue strength for laminated composites, as reported in [12]. In this case it would be necessary to investigate an effect of layers orientation with respect to the longitudinal direction X_A on the damage process in the composite pipe joint.

Next, the shear stresses $\tau_{RA(ad)}$ were plotted for different load cycles in order to present their redistribution during the crack-like damage propagation. They are collected in Figures 7, 8, 9 and 10. These shear stresses were determined in the middle of adhesive layer thickness and the crack-like damage tips on both sides of a joint are denoted by t and b.

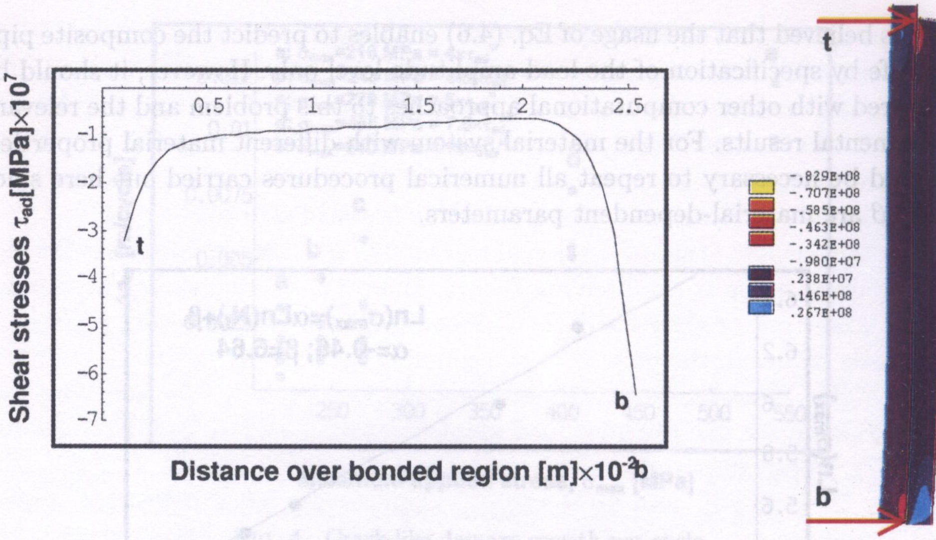

FIG. 7. Shear stresses in undamaged adhesive layer.

As it was expected, see Eq. (2.3), the maximum shear stresses increase together with the loading cycles number. It is caused by the fact that load transfer area from a pipe to the coupling monotonously decreases. The crack-like damage propagation is initially the same for both tips t and b as a consequence of similar shear stresses magnitudes; after that the shear stresses magnitudes change and are different at the opposite crack-like damage tips. It probably results from the non-uniform extension of the crack-like damage across the remaining adhesive

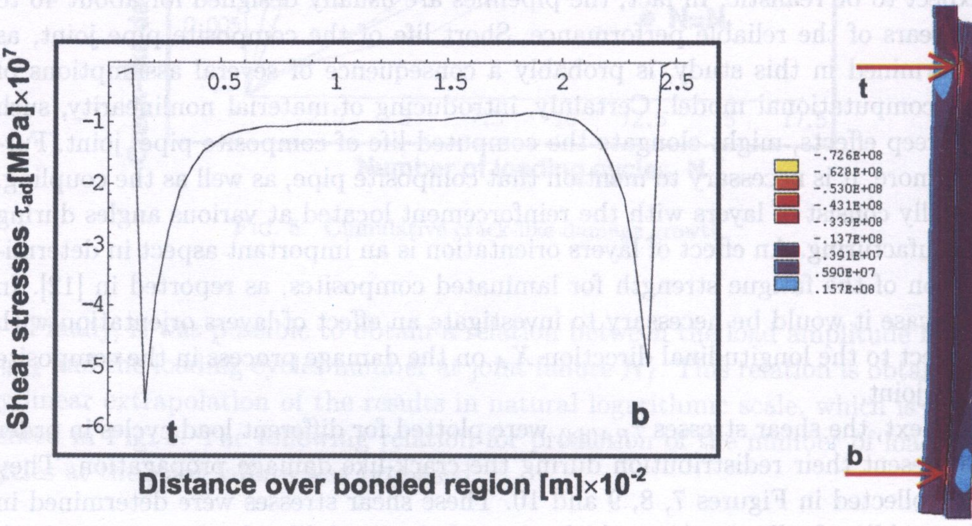

FIG. 8. Shear stresses in adhesive layer after 2 cycles (2 years).

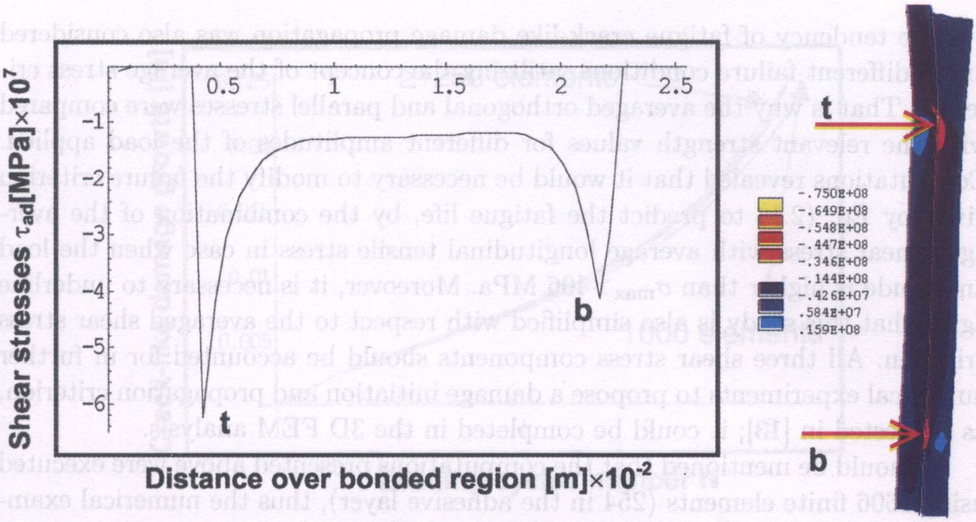

FIG. 9. Shear stresses in adhesive layer after 5 cycles (5 years).

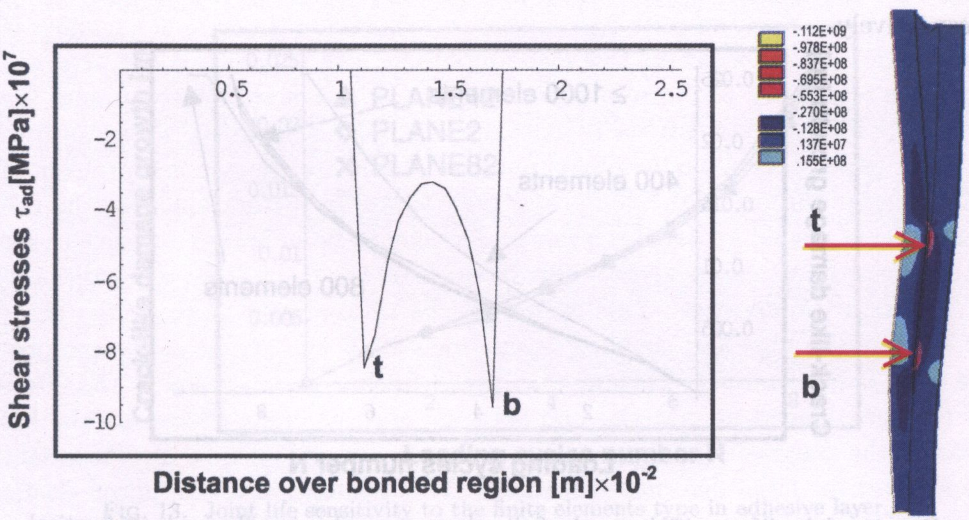

FIG. 10. Shear stresses in adhesive layer after 8 cycles (8 years).

layer. It is necessary to mention that prior to failure, lower part of a pipe overlapped coupling. It does not demonstrate a realistic situation where both the pipe and coupling would slide over each other. An increase of the stiffness of the damaged elements will probably avoid this situation, however it can also lead to an increase of stress transfer through those elements.

The tendency of fatigue crack-like damage propagation was also considered under different failure conditions, utilizing the concept of the average stress criterion. That is why the averaged orthogonal and parallel stresses were compared with the relevant strength values for different amplitudes of the load applied. Computations revealed that it would be necessary to modify the failure criterion given by Eq. (2.1) to predict the fatigue life, by the combination of the averaged shear stress with average longitudinal tensile stress in case when the load amplitude is higher than $\sigma_{\max}>406$ MPa. Moreover, it is necessary to underline again that this study is also simplified with respect to the averaged shear stress criterion. All three shear stress components should be accounted for in further numerical experiments to propose a damage initiation and propagation criterion, as suggested in [13]; it could be completed in the 3D FEM analysis.

It should be mentioned that the computations presented above were executed using 2606 finite elements (254 in the adhesive layer), thus the numerical examples have been undertaken next in order to estimate the total finite elements number effect on the results. It was assumed that finite element number in the adhesive layer may influence these results only. Thus, the vertical mesh division effect was studied first with 400, 800, 1200, 1600, 2000 and 4000 finite elements, respectively.

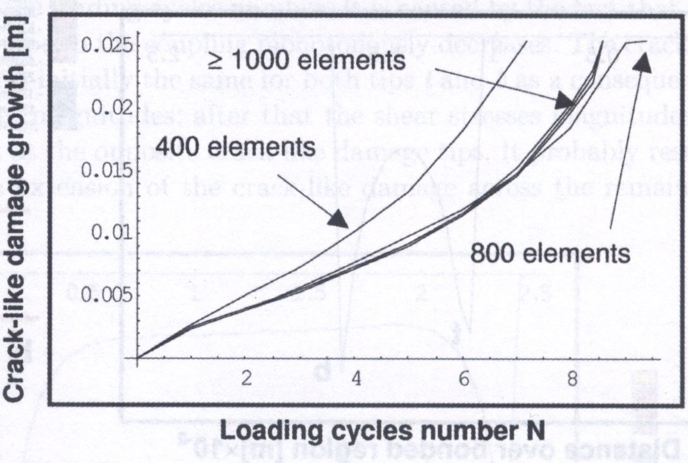

FIG. 11. Joint life sensitivity to the finite elements number in adhesive layer (vertical direction).

The results obtained became independent of the decreasing finite element size (cf. Fig. 11), while the finite element size, for which the results did not change, was equal to $l_e \approx 0.0001$ m. It corresponds to 250 vertical mesh divisions of the adhesive layer length considered. Computational results show that the element size simulating characteristic length d should be much smaller than that approximated by Eq. (2.2) and can be approximately equal to $d \approx 0.0007$ m.

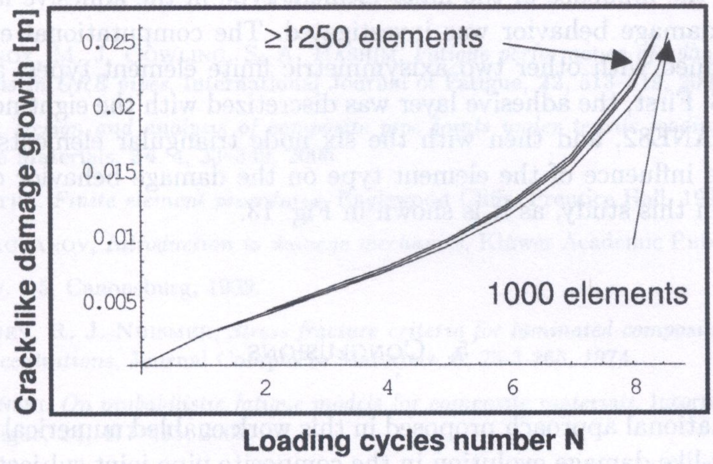

FIG. 12. Joint life sensitivity to the finite elements number in adhesive layer (vertical sensitivity).

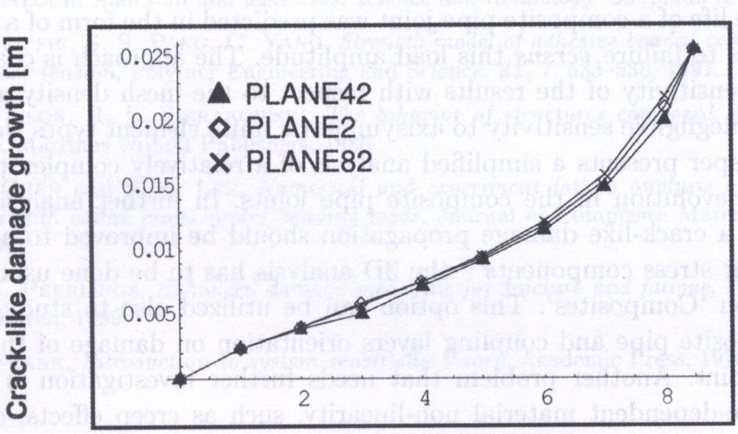

FIG. 13. Joint life sensitivity to the finite elements type in adhesive layer.

Similar comparative studies were carried out for different horizontal divisions and demonstrated a rather small mesh effect on fatigue life prediction, which oscillated between 8.4 and 8.6 load cycles number (cf. Fig. 12). The finite element mesh of this particular adhesive layer should be designed with at least 5×250 elements (horizontal $\times$ vertical ones) in order to avoid the mesh effect on the life prediction (hard to be predicted).

Finally, the influence of the finite element type in the adhesive layer on the composite damage behavior was investigated. The computational experiments were preformed with other two axisymmetric finite element types, available in the ANSYS. First, the adhesive layer was discretized with the eight node quadrilaterals PLANE82, and then with the six node triangular elements PLANE2. A negligible influence of the element type on the damage behavior of the joint was found in this study, as it is shown in Fig. 13.

5. Conclusions

Computational approach proposed in this work enabled numerical estimation of the crack-like damage evolution in the composite pipe joint subjected to axial static cyclic tension with constant amplitude. The computational analysis was elaborated using the FEM computer system ANSYS and its option 'Element Birth and Death'. This numerical approach led to the fully automatic crack-like damage propagation simulation without any re-meshing procedures. As the result, the life of a composite pipe joint was predicted in the form of a number of load cycles to failure *versus* this load amplitude. The approach is characterised by some sensitivity of the results with respect to the mesh density around the crack tip; negligible sensitivity to axisymmetric finite element types was verified.

The paper presents a simplified analysis of a relatively complex problem of a damage evolution in the composite pipe joints. In further analysis, the criterion for a crack-like damage propagation should be improved to account for other shear stress components – the 3D analysis has to be done using the ANSYS option 'Composites'. This option can be utilized also to study the effect of a composite pipe and coupling layers orientation on damage of the composite pipe joint. Another problem that needs further investigation is the effect of the rate-dependent material non-linearity, such as creep effects, on the life span of the composite pipe joint. As a consequence, it might be also necessary to account for large deformations effects. The assumption of the linear elastic material behavior can be a reason of non-realistic short life span of the joint. Another reason could be the damage localization connected with only two possible finite element damage status: damaged or undamaged – usage of non-local and gradient-enhanced damage mechanics formulations [14] can considerably improve the damage model. Next, the problem can be extended to the numerical analysis of a damage evolution under random material parameters and implemented in the framework of the Probabilistic Design System of ANSYS. For this purpose, the detailed sensitivity analysis [15] of the results to design variables, i.e. material parameters, should be carried out.

References

1. E. M. Knox, M. J. Cowling, S. A. Hashim, *Fatigue performance of adhesively bonded connections in GRE pipes*, International Journal of Fatigue, **22**, 513–519, 2000.
2. C. Yang, *Design and analysis of composite pipe joints under tensile loading*, Journal of Composite Materials, **34**, 4, 33–349, 2000.
3. K. J. Bathe, *Finite element procedures*, Englewood Cliffs, Prentice Hall, 1996.
4. L. M. Kachanov, *Introduction to damage mechanics*, Kluwer Academic Publishers, 1986.
5. ANSYS, v. 5.5, Canonsburg, 1999.
6. J. Whitney, R. J. Nuismer, *Stress fracture criteria for laminated composites containing stress concentrations*, Journal Composite Materials, **8**, 25-3-265, 1974.
7. M. Kamiński, *On probabilistic fatigue models for composite materials*, International Journal of Fatigue, **24**, 477–495, 2002.
8. V. V. Bolotin, *A unified approach to damage accumulation and fatigue crack growth*, Engineering Fracture Mechanics, **22**, 3, 38–398, 1985.
9. C. Zweben C., H. T. Hahn, T.-W. Chou [Eds.], *Delaware composites design encyclopedia*, **1**, 47–70, Lancaster, Technomic Publishing Co., 1989.
10. A. J. Kinloch, *Adhesion and adhesives: science and technology*, Chapman & Hall, 1987.
11. S. A. Griffin, S. S. Pang, C. Yang, *Strength model of adhesive bonded composite pipe joints under tension*, Polymer Engineering and Science, **31**, 7, 533–538, 1991.
12. J. R. Vinson, R. L. Sierakowski, *The behavior of structures composed of composite materials*, Martinus Nijhoff Publishers, 1986.
13. W. H. Chen and S. S. Lee, *Numerical and experiment failure analysis of composite laminates with bolted joints under bending loads*, Journal of Composite Materials, **29**, 1, 15–36, 1995.
14. R. H. J. Peerlings, *Enhanced damage modelling for fracture and fatigue*, PhD Thesis, TU Eindhoven, 1999.
15. P. M. Frank, *Introduction to system sensitivity theory*, Academic Press, 1978.

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