FAILURE MODES IN COMPOSITE JOINTS
A FINITE ELEMENT STUDY

Efstathios E. Theotokoglou

Department of Engineering Science, Section of Mechanics
The National Technical University of Athens
GR-157 73 Athens, Greece

SUMMARY: The aim of this paper is to improve the efficiency of T-Joints placed in high speed marine vessels. The behaviour of such joints is very complex since it involves several types of materials such as GRP, foam material as well as glue filler. The material and geometry discontinuities cause stress concentrations in T-joints which can initiate interlaminar or fatigue cracks. A crack propagating between the connected laminate and the attachment lap has been evaluated using the crack flank displacement method in conjunction with the finite element method. Numerical results are presented for the stress intensity factors in the case of T-joints subjected to lateral loads.

KEYWORDS: fibre reinforced plastic, T-joints, sandwich material, GRP-laminates, interface crack, finite element analysis, stress intensity factors.

INTRODUCTION

The Use of FRP (Fibre Reinforced Plastic) sandwich materials for large maritime vessels has in the past years increased enormously, due to the mechanical advantages of the material, especially the high strength/stiffness to weight ratio, high dynamical damping and low thermal conductivity [1].

Apart from the above-mentioned advantages of the FRP sandwich material, one of the major mechanical drawbacks is the difficulty of joining sandwich panels. In maritime vessels such sandwich panel joints occur in very large numbers where the T-joint between hull and bulkhead is the most prelevant connection type. Due to the fact that the FRP face laminates of the sandwich structure are usually thin, the introduction of concentrated point or line loads leads to inexpedient local disturbances [2,3].

A traditional hull-bulkhead T-joint geometry is shown in Figure 1. The design of the connection is primarily based on considerations of the manufacture. The T-joint is composed of a PVC-core and GRP-laminates based on E-glass and polyester. The two panels are kept together with glue in the contact face together a GRP-attachment lap outside the laminates (Fig. 1). To investigate the influence of the attachment lap on the failure load of the typical hull-bulkhead connections, a series of experiment tests have been carried out in [4,5]. All test specimens were loaded until failure. From the experiments, the dominant failure-mechanism was failure between the panel laminates the glue and the attachment lap. It was characteristic of all the test specimens that a delamination between the connection laminate and the face laminate of the hull panel, had finally taken place.

From the experimental investigation of the T-joint specimens loaded to failure, it was found that the material discontinuities cause stresses concentration in the T-joints which might result in initial interlaminar cracks or initiation of small fatigue cracks. Furthermore, in the hull of a sandwich ship, large panel sections are joined, and during the fabrication the probability of introducing cracks is almost 100%. These cracks can grow during a fatigue loading and cause failure of the whole structure.

To investigate the influence of such interlaminar cracks, a numerical fracture mechanics analysis has been carried out in this study for different attachment laps of the T-joint, based on a **finite element** discretized modelling of the T-joint. In particular, the stress intensity factors for interface cracks between dissimilar materials have been calculated using the Finite Element Method in connection with a method proposed by Smelser [6].

THE T-JOINT DESIGN AND FAILURES MODES

A traditional hull-bulkhead T-joint geometry is shown in Figure 1. The design of the connection is primarily based on considerations of the manufacture. The T-joint is composed of a PVC-core and GRP-laminates based on E-glass and polyester. The two panels are kept together with glue in the contact face together with a GRP-attachment lap outside the laminates (Fig.1). The face sheets of the sandwich panels consist of two layers of $800\,g/m^2$

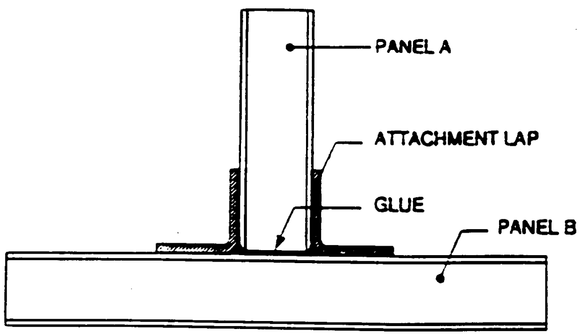

Fig. 1: *Connection between two sandwich beams*

each, woven roven E-glass with fibers in ± 45 directions and $150\,g/cm^2$ Chopped Strand Mat (CSM) on top and on bottom of the laminates. One layer of standard AI-reinforcement consists of $400\,g/m^2$ woven roven E-glass with fibers in ± 45 directions and $100\,g/m^2$ CSM on top of the laminate. The mechanical properties of the laminates and of the attachment lap are given in Table 1. The glue material used is Crestomer 1152 PA and the core material is PVC-foam, Divinycell H100. Their mechanical properties are given in Tables 2 and 3.

Table 1 : *Mechanical Properties of E-Glass Polyester Laminate [4]*

Longitudinal/Transverse Young's modulus (MPa)	10000/10000
Shear modulus (MPa)	6200
Longitudinal/Transverse tensile strength (MPa)	95/95
Longitudinal/Transverse compressive strength (MPa)	123/123
Shear strength (MPa)	93

Table 2 : *Typical Properties of Crestomer 1152 PA [7]*

Ultimate tensile strength (MPa)	26
Elongation at break (%)	100
Initial tensile modulus (MPa)	500
Yield stress at 7% strain (MPa)	17

Table 3 : *Mechanical Properties of Divinycell PVC H100 at 20^{o}C [8]*

Density $\left(kg/m^3\right)$	102
E-modulus compression, ASTM D1621 (MPa)	130
Ultimate compressive strength, ASTM D1621 (MPa)	1.7
E-modulus tension, ASTM D1623 (MPa)	105
Ultimate tensile strength, ASTM D1623 (MPa)	2.8
Shear modulus at 20^{o}C, ASTM C273 (MPa)	40
Ultimate shear strength, ASTM C273 (MPa)	1.5

To investigate the influence of the attachment lap on the failure load of the typical hull-bulkhead connections, a series of experimental tests have been carried out in [4]. All test specimens were loaded unit failure. From the experiments, the dominant failure-mechanism was failure between the panel laminates the glue and the attachment lap. It was characteristic of the test specimens that a crack was initiated at the end of the fillet material of the singular point at which the bonded tape laminate is connected to the face laminate of the hull panel. Once the crack opens it will propagate along the interface between the connected laminate and the fillet to a certain point at which the crack started to kink into the fillet material and between the connection laminate and the face laminate resulted finally delamination. In our previous studies [4,5] we have examined the strength of composite T-joints without considering any crack in the glue-fillet area. In this study a crack is considered between the connected laminate and the fillet material and the stress intensity factors are calculated using the linear finite element method in connection with the displacements of the crack flanks in the vicinity of the crack tip.

DETERMINATION OF THE STRESS INTENSITY FACTORS

Let a medium (Fig.2) with elastic properties μ_1 and ν_1 occupy the lower half plane, and a medium with elastic properties μ_2 and ν_2, occupy the upper half plane, where $\mu_k(k=1,2)$ is the shear modulus, ν_k being the Poisson's ratio and $\kappa_k = 3-4\nu_k$ for plane strain, $\kappa_k = (3-\nu_k)/(1+\nu_k)$ for generalized plane stress

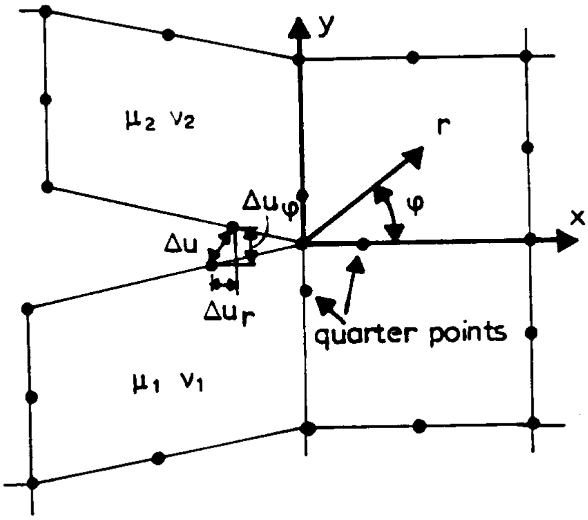

Fig. 2: *Geometry and local coordinates for analyzing the displacement field close to the crack tip.*

According to Schmelser [6], the complex crack opening Δu is defined as

$$\Delta u = |\Delta u| e^{i\grave{E}} \tag{1}$$

where the angle $\grave{E}$ is given by

$$\grave{E} = \varepsilon \ell n r - \beta - \delta - \pi/2 \tag{2}$$

with

$$\varepsilon = \frac{1}{2\pi} \ell n \left(\frac{\mu_1 + \mu_2 \kappa_1}{\mu_2 + \mu_1 \kappa_2} \right) = \frac{1}{2\pi} \ell n(\gamma) \, , \delta = \tan^{-1}(2\varepsilon) \, , \tag{3}$$

and

$$k = k_0 e^{i\beta} = k_I + i k_{II} \tag{4}$$

the complex stress intensity factor.

Finally, it is obtained [6]

$$\Delta u = \frac{1}{4\sqrt{2}} \left(\Lambda_1 + \Lambda_2 \right) \frac{k}{\lambda} r^{\lambda} e^{-i\pi/2} \tag{5}$$

where

$$\Lambda_i = \begin{cases} \dfrac{4(1-\nu_i)}{\mu_i} & plane\ strain \\ \dfrac{4}{\mu_i(1+6\nu_i)} & plane\ stress \end{cases} \tag{6}$$

and, the strength of the singularity λ for a crack between the two dissimilar media is given by

$$\lambda = \frac{1}{2} + i\varepsilon \tag{7}$$

and; it may be expressed as

$$\lambda = \lambda_0 e^{i\delta} \tag{8}$$

where

$$\lambda_0 = \sqrt{\frac{1}{4} + \varepsilon^2} \tag{9}$$

Taking into consideration relations (4) and (8), the magnitude of the crack opening is given by

$$|\Delta u| = \frac{1}{4\sqrt{2}}\left(\Lambda_1 + \Lambda_2\right)\frac{k_0}{\lambda_0}\sqrt{r} \tag{10}$$

and the angle $\grave{E}$ is given by relation (2) or by the following relation

$$\grave{E} = \tan^{-1}\left(\frac{\Delta u_\varphi}{\Delta u_r}\right) \tag{11}$$

where $\Delta u_\varphi, \Delta u_r$ are defined in Figure 2. Substituting equation (11) into equation (2), the angle β of the stress intensity factor (relation (4)) can be found

For different r the corresponding pair of nodes along the crack flanks close to the crack tip can be used in order to calculate k_0 (relation (10)). Having determined k_0 the stress intensity factors at the crack-tips of an interface crack are yielded.

FINITE ELEMENT MODEL

The above described procedure has been used for a number of T-joint geometries to analyze a crack in the interface between the fillet and the connected laminate. The analyzed geometries are identical to the geometries used at the experimental tensile tests [4]. Taking into consideration the symmetry only the half of the T-joint is analyzed using the Finite Element Method. The dimensions of the T-joint and the imposed constraints are shown in Figure 3.The radius ρ of the attachment lap in the glue-fillet area is taken to be $(145+t)mm$, where t is the thickness of the lap ($t=0525$ for one layer in the lap). The finite element analysis is performed with the use of the general purpose finite element program ANSYS [9]. Plane strain is assumed throughout and the finite element mesh consists of plane isoparametric elements with eight nodes. Quadrilateral Quarter Point elements are used close to the crack-tip to get a proper stress distribution (Fig. 2).

The analysis is carried out for T-joints subjected to a tensile load of $28(KN)$ applied to the bulkhead. This load is relevant to the first load obtained by the experimental tests of the T-joints considered in [4,5].

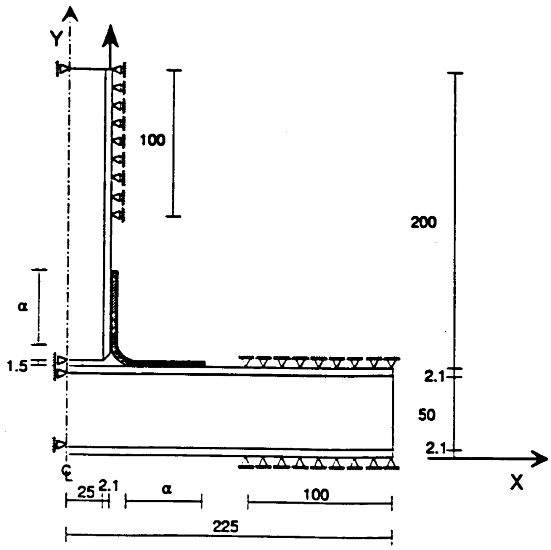

Fig. 3: *Overall model with boundary conditions*

NUMERICAL ANALYSIS AND CONCLUDING RESULTS

In the finite element analysis a crack is placed in the interface between the fillet and the connected laminate (Fig. 4). The crack is then propagated along the interface. The propagation is performed by changing the node coordinates for the four Quadrilateral Quarter Point elements which formed the crack-tip. Six steps are performed each time evaluating the stress intensity factors K_I and K_{II}.

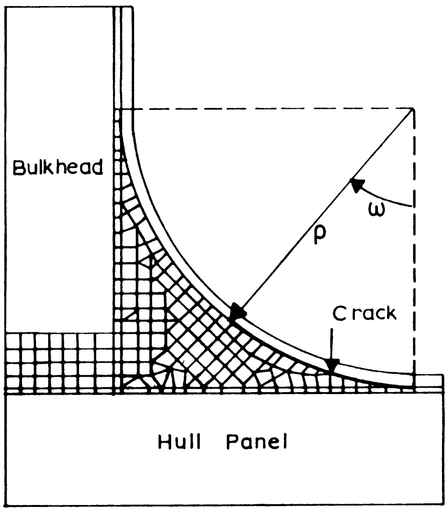

Fig.4: *Model of the crack propagation in the glue-fillet area*

In Table 4 the K_I,K_{II} stress intensity factors are plotted in terms of the angle ω (Fig. 4). When ω is around 55°, the sign for K_I changed from positive to negative. This indicates that crack closure is taking place. When crack closure occurs, the interface crack is no longer propagated between the connected laminate and the fillet material but it starts to kink into the fillet material, as it is also provided from the experiments.

Table 4: *Stress intensity factors* K_I, K_{II} *as a function of the angle* ω *of T-joints subjected to lateral loads in the case of three layers in the lap.*

Extension α of the lap (m)	Angle ω	K_I $(MPa\sqrt{m})$	K_{II} $(MPa\sqrt{m})$
0.08	25°	4.50	-0.93
0.06	25°	4.51	-0.92
0.08	35°	4.90	-3.81
0.06	35°	4.90	-3.80
0.08	45°	2.00	-4.90
0.06	45°	2.01	-4.90
0.08	55°	-0.56	-4.00
0.06	55°	-0.56	-3.98

From our analysis it follows that the values of the opening-mode and shear-mode stress intensity factors are independent from the extention of the lap. Therefore in the case of static tests, the failure load is independent of this design parameter. The above numerical analysis is performed considering linear fracture mechanics analysis. A similar analysis has been performed in [10] in the case of fatigue loading. Glue is a material that yield plastically, so further research is required in order to predict the overall behaviour of the T-joint more exactly.

REFERENCES

1. Smith C.S., *Design of Marine Structures in Composite Materials*, Elsevier Applied Science, London 1990.
2. Allison, I.M., Localized loading of sandwich beam, *in Proceedings of the 9'th International Conference on Experimental Mechanics*, Copenhagen, Denmark, 1990, pp. 1604-1609.
3. Thomsen, O.T., Further remarqs on local bending analysis of sandwich panels using a two parameter elastic foundation, *Report No.40*, Aalborg University, Institute of Mechanical Engineering, 1992.
4. Theotokoglou E.E. and Moan, T., Experimental and Numerical Study of Composite Tee-Joints, *Journal of Composite Materials*, Vol. 30, 190-209 (1996).
5. Theotokoglou E.E., Strength of Composite T-Joints under Pull-Out Loads, *Journal of Reinforced Plastics and Composites*, Vol. 16, 503-518 (1997).
6. Smelser R.E., Evaluation of Stress Intensity Factors for Bi-material Bodies using Flank Displacement Data, *International Journal of Fracture*, Vol. 15, 135-143, 1979.
7. Scott Bader Company Limited. *Technical leaflets No. 957 and 958* (Wolleston, Northamptonshire, NN9 7RL).
8. Barracuda Technologies A/S (P.O. Box 228, Nye Vakasvei 78, N-1364 Hvalstad, Norway)
9. Users Manual for ANSYS, Swansan Analysis Systems, Houston, PA (1990).
10. Burchardt, "Bonded sandwich T-Joints for Maritine applications" *Proceedings of the Second North European Engineering and Science Conference (NESCoII),* Stockholm, Sweden, 22-23 October 1997, Backlund, J., Zenkert D. and Astron B.T., Eds, pp. 175-192.