# Damage prediction models for composite T-Joints in marine applications

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**Abstract:** For a monocoque hull structure, the bulkhead is used to separate the hull into many compartments. A typical joint between the hull and bulkhead used in such structure is known as a T-joint. It consists of composite overlaminates over a shaped fillet to allow the transmission of direct and membrane shear stresses. This paper describes the numerical solutions of the analytical approach in studying of the effect of disbond for a composite ship T-Joint using two methods, the VCCT (Virtual Crack Closure Technique) and CTE (Crack Tip Element) method. The analysis was conducted for T-Joints with various disbond sizes. It was subjected to a straight pull-off load to simulate normal operational conditions. An experimental investigation was conducted to validate the FE (Finite Element) models. The results of the numerical and experimental studies are discussed to corroborate the effectiveness of using fracture mechanics for this analysing this structure. A modified CTE model for the T-joint is proposed to enable a like-for-like comparison to that evaluated by the VCCT method.

**Keywords:** CTE - crack tip element, Fracture, LEFM - linear elastic fracture mechanics, T-joint, VCCT - virtual crack closure technique.

## 1 Introduction

The hull is the main part of a ship structure and its design or construction method is different from ship to ship. For a Monocoque hull structure, the bulkhead is used to separate the hull into many compartments. It also provides rigidity and strength under transverse load. The connection between bulkhead and hull should allow transmission of direct and membrane shear stresses and it structural member is called a T-Joint. It consists of composite overlaminates over a shaped fillet constructed by stacking up layers of laminates through hand lay-up process, as shown in Figure 1.

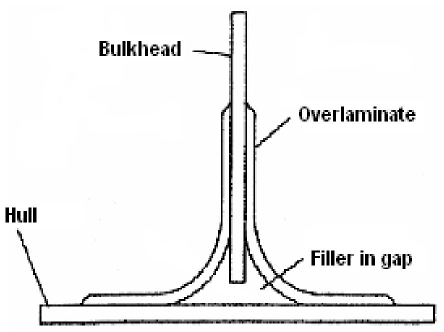



Figure 1 A circular T-Joint adapted from [1]

In this paper, the accuracy and applicability of FE (Finite Element) analysis to determine the damage criticality of a structure is investigated. Two FE based analytical methodologies, VCCT (Virtual Crack Closure Technique) and CTE (Crack Tip Element) were compared. The 2D VCCT analysis in [2] assumes that the disbond tip is straight along the depth (Y-axis), which holds true for uniform loading. For variable loading however, the crack tip may not form a straight line along the depth; hence it requires the CTE or 3D VCCT methods for the investigation. In this case, the CTE has an advantage over the VCCT method, because the CTE method can use 2D shell elements, rather than 3D solid elements to model 3D delamination problems.

The damage configuration chosen was a horizontal disbond between the hull and the overlaminate as it is one of the critical parts in the T-Joint [1]. The length of the horizontal disbond varied from 30, 60 and 90 mm to ensure the consistency of both methods. The results obtained using VCCT and the experimental results had been reported previously [2]. Therefore, this paper will focus more on the analysis and results obtained from the CTE technique.

## 2 Finite element analysis

All T-Joint FE models presented were constructed using MSC.Patran and analysed with MSC.Nastran software. The dimensions of the FE model are given in Figure 2. The hull, bulkhead and overlaminate sections were modelled using orthotropic properties, while the filler material was modelled using isotropic properties as shown in Table 1.

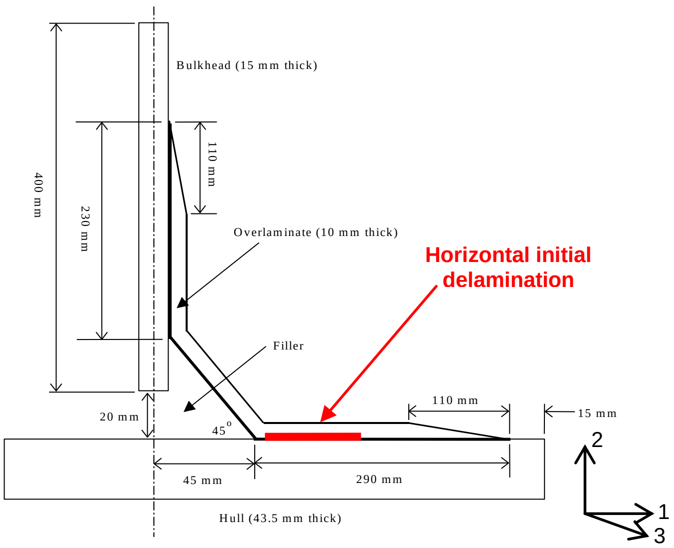



Figure 2 Dimensions of symmetrical half of the T- joint [2]

Table 1 Material properties for T-Joint FE models [2]

| T-Joint parts<br>Materials<br>Manufacturing method | Hull, Bulkhead<br>800 GSM Woven<br>VARTM | Overlaminate<br>800 GSM Woven<br>Hand lay-up | Filler<br>Milled Glass in<br>Vinylester |
|---|---|---|---|
| $E_1$ (GPa) (Warp) | 26.1 | 23.5 | 3.5 |
| $E_2$ (GPa) (Interlaminar) | 3.0 | 3.0 | |
| $\nu_{12}$ | 0.165 | 0.165 | 0.3 |
| $G_{12}$ (GPa) | 1.5 | 1.5 | 2.0 |
| $G_{13}$ (GPa) | 3.34 | 2.86 | |
| $G_{23}$ (GPa) | 1.5 | 1.5 | |

### 2.1 *Virtual Crack Closure Techniques (VCCT)*

The T-Joint was modelled using 2-dimensional (2D) 4-noded shell element in plane stress with a depth of 5 mm based on previous work by Dharmawan *et al.* [3]. The FE model was loaded with a static pull-off force of representative of normal operational loading [4]. Pinned-slide boundary conditions were applied at the nodes with the distance of 225 mm from the centre of the structure as shown in Figure 3.

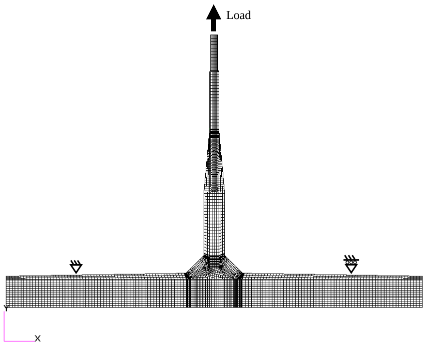



Figure 3 FE model of a T-joint with loading and boundary conditions [2]

The detail of the VCCT method may be found in [5]. Figure 4 shows the formula used for VCCT. Mode I and II components of SERR (Strain Energy Release Rate), $G_I$ and $G_{II}$ were obtained using the nodal forces and displacements behind as shown in Figure 4.

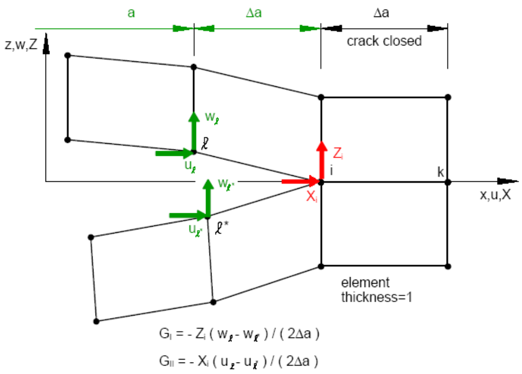



Figure 4 VCCT formulae for four-noded Quad elements [5]

## 2.2 *Crack Tip Element*

Davidson [6, 7] developed a methodology to predict delamination growth for aerospace structures using LEFM (Linear Elastic Fracture Mechanics) theory and CLPT (Classical Laminate Plate Theory), which is called the CTE (Crack Tip Element) approach. Apart from a significant decrease in computational time, this approach is also a proven crack growth prediction technique for composite laminates, where oscillatory singularity exists in the crack tip [6, 7]. A 3D CTE, as shown in Figure 5 utilises the centroid CLPT forces and moments of the short segments adjacent to the crack tip to determine the total SERR (Strain Energy Release Rate), $G_T$ and its components, $G_I$, $G_{II}$, $G_{III}$. The short segments are very small in comparison of the overall structure, hence they are regarded as elements adjacent to the crack tip, or crack tip elements. CTE theory described in this report is explained by Davidson [8]. From Figure 5, the area directly above the cracked plane refers to as plate 1, while plate 2 corresponds to the area directly below the cracked plane. The area behind the crack tip is called uncracked region and vice versa. All the superscripts on the loadings refer to the region of the plates. The origin of the coordinate system used is located at the crack tip at the mid-plane of the uncracked region. N and M symbolize the centroid forces and moments at the respective plate and region. The subscripts used for N and M correspond to the direction of the forces and moments based on the CLPT convention. Therefore, the subscript 1 represent the x direction (axial) and 6 the x,y direction (shear). The t and w signify the thickness and width of the element. The dimension, a and b represent the element length of the cracked and uncracked region respectively. The CTE theory assumes that the elements length (a,b) and width (w) are much larger ($\geq$ *8 times)* compared to the total thicknesses (t), loadings of the plate are remote from the crack tip and mid-plane slope of the plate is only due to the bending moment as assumed in CLPT [7].

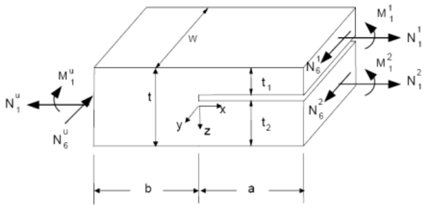



Figure 5 3D CTE and its loading [7]

The following Equations ( 1 ) to ( 4 ) show the formulae in determing $G_T$ (Total Elastic Energy Release Rate) and its components [7]. From Equation ( 1 ), $i = 1,2,6$ refers to the direction of the mid-plane strain and curvature as well as forces and moments as defined in the CLPT. The symbol $j = 1,2$ corresponds to plate 1 and 2, above and below crack plane respectively. The quantities in Equation (1), $N, M, \varepsilon, \kappa$ are the mid-plane forces, moments, strain and curvature as defined by CLPT respectively and located at the centroid of the four elements adjacent to the crack tip. $N_c$ and $M_c$ in equation (2) and (3) are concentrated crack tip forces and moments. They are functions of the CLPT forces and moments of the crack tip elements, material properties and plate element geometry [8]. The quantities $c_{11}$, $c_{22}$, $\Gamma'$ are functions of material properties and laminate lay-up [7]. $\Omega$ is the mode mix parameter, which determines the magnitude of $G$ correspond to each mode. In addition, the value of $\Omega$ is independent of the loading and $G_T$ is independent of $\Omega$ [7]. Only $G_I$ values will be considered in this paper.

$$G = \frac{1}{2}\sum_{j=1}^{2}\left(\Delta N_i \Delta\varepsilon_i^0 + \Delta M_i \Delta\kappa_i\right)_j \text{ , } i = 1,2,6 \qquad (1)$$

$$G_I = \frac{1}{2}\left[-\sqrt{c_{11}}N_c' \sin\Omega + \sqrt{c_{22}}M_c' \cos\left(\Omega + \Gamma'\right)\right]^2 \qquad (2)$$

$$G_{II} = \frac{1}{2}\left[\sqrt{c_{11}}N_c' \cos\Omega + \sqrt{c_{22}}M_c' \sin\left(\Omega + \Gamma'\right)\right]^2 \qquad (3)$$

$$G_{III} = G - G_I - G_{II} \qquad (4)$$

Based on the CLPT assumption mentioned above, CTE approach will not apply for the current T-Joint structure (Figure 2) due to its thickness and width/length ratio. Table 2 shows the allowable maximum thickness that corresponds to each delamination length in order to meet CLPT assumption. The characters H, O, B represent the hull, overlaminate and bulkhead respectively. The subscript "ply" represents the ply quantities for each part. The ply thickness of hull and bulkhead is 0.64 mm, while the overlaminate is 0.79 mm. The comparison analysis will utilise the maximum allowable thickness for each different disbond length. The different $\mathbf{t_{max}}$ values used for the disbond length of 60 and 90 mm was to demonstrate the robustness of the method.

Table 2 New thicknesses correspond to the different delamination sizes

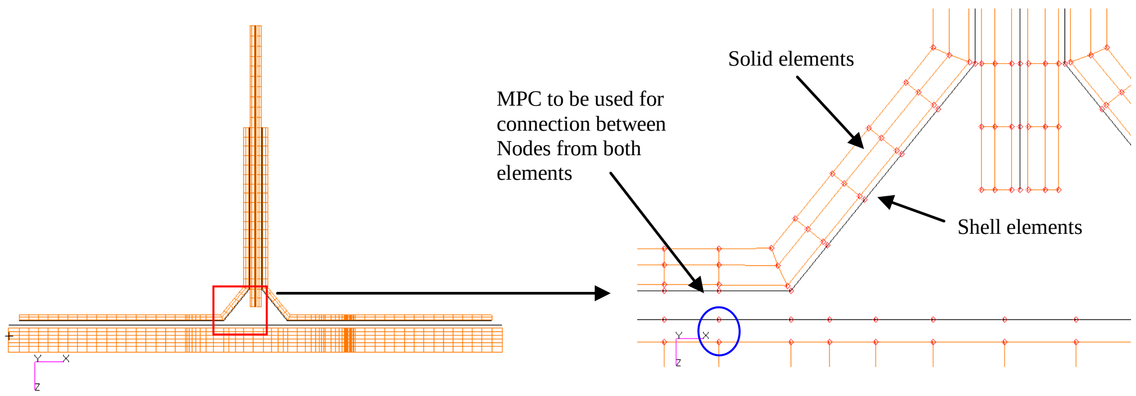
| **Disbond length (mm)** | $\mathbf{t_{max}}$ **(mm)** | $\mathbf{H_{ply}}$ | $\mathbf{O_{ply}}$ | $\mathbf{B_{ply}}$ | $\mathbf{t_H}$ **(mm)** | $\mathbf{t_O}$ **(mm)** | $\mathbf{t_B}$ **(mm)** |
|---|---|---|---|---|---|---|---|
| 30 | 3.75 | 5 | 1 | 2 | 3.20 | 0.79 | 1.28 |
| 60 | 7.5 | 10 | 2 | 3 | 6.40 | 1.58 | 1.92 |
| 90 | 11.25 | 14 | 3 | 5 | 8.96 | 2.37 | 3.20 |

In exploring the applicability of the CTE method for the current T-Joint structure, the thin T-Joint structure must be used in order to meet the CLPT assumption, yet the similarity of stiffness between the modified and original structure must be ensured for comparison purposes. The material properties cannot be altered, since it will affect the CLPT stiffness matrix, thus the calculation to obtain $G$ values. Therefore, it was proposed that the thin T-Joint was attached to 3D solid elements to form the original T-Joint dimensions as shown in Figure 2.

The resulting FE model for the CTE analysis with the attachment with solid elements is shown in
(a) (b)
**Figure 6** below. The zoomed-in view of
**(a)** **(b)**
**Figure 6** shows the section around the left hand side of the overlaminate section. Each 2D element is attached to the 3D solid elements using MPCs (Multi-Point Constraints) to ensure similar displacement and force transfer. The black line in
**(a)** **(b)**
**Figure 6**, which is indicated as shell elements is shown clearly in

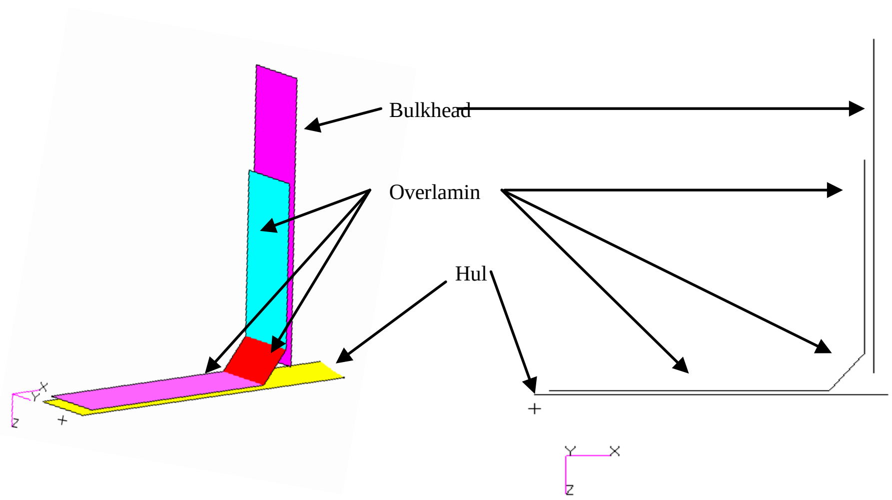
(a) (b)

**Figure** 7. The fillet was left empty in order to simplify the application of the CTE method. Therefore, the filler material in the T-Joint created with VCCT for this comparison analysis will also be removed for consistent comparative reasons.




(a) (b)

Figure 6 The thin T-Joint model (Front view) attached with 3D solid elements (a) full view (b) zoom view



(a) (b)

Figure **7** Symmetrical half of T-Joint FE model created using shell elements before its attachment to the solid elements (a) isometric view (b) front view

## 3 Results and discussions

Previous work [2] showed that VCCT technique (filler material included) did accurately predict the failure load of the T-Joint through the determination of the *G* values and it is shown in Table 3 below. Hence, the comparison of *G* values using VCCT results was sufficient in order to determine the accuracy of the CTE method.

Table 3 Comparison of failure load obtained from FE (VCCT) and experiment [2]

| Disbond length (mm) | Failure Load (KN) | | |
|---|---|---|---|
| | Experimental | FE | % Difference |
| 30 | 13.5 | 12 | -11% |
| 60 | 13.4 | 10.3 | -23% |
| 90 | 7.2 | 6.8 | -6% |

The result obtained from the modified T-Joint using the CTE method (without filler material) can be viewed in

Table **4** below. Note that the analysis results using VCCT shown in

Table **4** is also without the filler material.

Table 4 Mode I fracture toughness obtained from the CTE & VCCT methods

| **FE model (based on disbond length)** | $G_{I\_CTE}$ **(J/m²)** | $G_{I\_VCCT}$ **(J/m²)** | **% difference =** $\frac{G_{I\_VCCT} - G_{I\_CTE}}{G_{I\_VCCT}} x100\ \%$ |
|---|---|---|---|
| 30 mm | 1200 | 1533 | 21.7 |
| 60 mm | 2083 | 2149 | 3.1 |
| 90 mm | 2872 | 2173 | -32.2 |

The results obtained from CTE method shows a reasonable agreement with VCCT results. Therefore, the CTE method can also be applied for a thick structure as long as the CLPT assumptions are met. However, for the current analysis, relatively significant computational effort was required to accommodate the large amount of solid elements to form the T-Joint. Hence, if the thick structure required had other dimensions in proportion to that comparable to the CLPT assumptions, the CTE analysis can simply be applied without any modification. It will reduce the computing requirement significantly by obviating the need for including solid elements.

## 4 Conclusions

The CTE method can be used to estimate fracture toughness parameters of structures such as *G*, as long as the CLPT dimension requirements are met as shown in our effort here. With the modifications shown, the computational effort for the CTE application in a thick structure is still quite large. However, this effort will be much less than if no solid element were used provided the CLPT requirements are met. This result confirms the tentative applicability of the CTE method to a wider class of structure types. To ensure general applicability of the CTE method to thick structures, some amendments to the original formulative CTE equations may be required.

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