CHAPTER 4

RESERVE CAPACITY OF FATIGUE DAMAGED
INTERNALLY RING STIFFENED TUBULAR JOINTS

4.1 EXPERIMENTAL INVESTIGATIONS

Damage to offshore structures endangers their integrity. Therefore, assessment of the residual strengths of the damaged structures assumes significance in the context of taking a decision on repairing the impaired structures and restoring them back to their original conditions. This will enable the structures to continue to serve the intended functions for the specified design life. A number of investigations have been carried out on the assessment of the reserve capacities of dent and bend damaged simple tubular members (Thandavamoorthy et al 1995 a, b; 1998). However, information on techniques for the evaluation of corrosion fatigue damaged tubular joints are lacking. Especially, little is known on the method of assessment of the fatigue damaged tubular joints, that are stiffened internally with three annular rings. Data on the reserve capacities of the fatigue damaged internally ring stiffened tubular joints are all the more essential to formulate guidelines for the evaluation of damaged condition. This aspect has not been addressed by any of the existing design codes. Therefore, there is a greater need to understand the behaviour of fatigue damaged internally ring stiffened joints under different types of loading and in this process to generate a database. This will facilitate to a great extent in developing a methodology to assess the residual strengths of the fatigue damaged internally ring stiffened tubular joints and also help in validating it with experimental results. Towards this goal, experimental investigations
were carried out to determine the reserve capacities of corrosion fatigue damaged internally ring stiffened tubular T and Y joints.

A number of fatigue damaged tubular joints, stiffened internally with three annular rings, were already available at the Fatigue Testing Laboratory of the Structural Engineering Research Centre, Madras. Test specimens required for the present investigation were selected from out this lot. The geometrical configurations of the selected typical internally ring stiffened damaged joints are shown in Fig. 4.1 for T joint and in Fig. 4.2 for Y joint. Three annular rings have been welded to the inside of the chord member and at the intersection of the brace. Each annular ring was 12 mm thick and 75 mm width. One ring has been welded at the centre of the brace and each of the remaining two at either face of the brace. The dimensions of both T and Y joints, such as the outside diameter of the chord and brace members and their thicknesses, are given in Table 4.1. The ends of the chord and brace members were sealed by 32 mm thick flange plates to facilitate mounting of the specimen in the test set-up.

While the diameters of the chord and the brace members given in Table 4.1 are measured values, the thicknesses are nominal ones since it was not possible to measure them. The material qualities of both chord and brace members are API5L GB and IS226 (1975) with the yield strength of 240 MPa and Ultimate Tensile Strength 415 MPa. Three numbers of fatigue damaged stiffened T joints and five Y joints were selected for testing in the present investigation.

These joints had earlier been tested under axial brace tensile fatigue loading under corrosive environments of sea water, synthesized according to the ASTM Standards D 1141 (ASTM 1980). Due to the synergetic action of fatigue and corrosion, these joints have developed through-thickness crack at the weld toe. The crack was formed on the top side of the chord member along its circumference. The length of the
Fig. 4.1 Typical Fatigue Damaged Stiffened T joint

6 HOLES OF 33 φ
RING STIFFENER
12 mm THK.
75 mm WIDTH
8 HOLES OF 26.5 φ
CRACK

320 PCD
219.00
32
18.00
600

FRONT VIEW

SECTION - AA

PLAN

RING STIFFENER
Fig. 4.2 Typical Fatigue Damaged Stiffened Y joint
circumferential crack for each selected T and Y joint was measured and is given in Table 4.1. The extent of the damage varied from 35 to 50 percent. Because of the aggressive environment, corrosion patches have been formed in the vicinity of the welded intersection of brace and chord members. However, there was no significant reduction in the wall thicknesses.

Table 4.1 Dimensions of the Damaged Stiffened Tubular T and Y Joints

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Specimen No.</th>
<th>Dimensions of the joint (mm)</th>
<th>Length of the circumferential crack (mm)</th>
<th>Quadrants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Chord</td>
<td>Brace</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diameter</td>
<td>Thickness</td>
<td>Diameter</td>
</tr>
<tr>
<td>1</td>
<td>DT1</td>
<td>320.00</td>
<td>12.00</td>
<td>219.00</td>
</tr>
<tr>
<td>2</td>
<td>DT2</td>
<td>316.72</td>
<td>12.00</td>
<td>221.54</td>
</tr>
<tr>
<td>3</td>
<td>DT3</td>
<td>320.54</td>
<td>12.00</td>
<td>218.68</td>
</tr>
<tr>
<td>4</td>
<td>DY1</td>
<td>319.86</td>
<td>12.00</td>
<td>220.50</td>
</tr>
<tr>
<td>5</td>
<td>DY2</td>
<td>320.27</td>
<td>12.00</td>
<td>221.23</td>
</tr>
<tr>
<td>6</td>
<td>DY3</td>
<td>321.27</td>
<td>12.00</td>
<td>219.80</td>
</tr>
<tr>
<td>7</td>
<td>DY4</td>
<td>320.68</td>
<td>12.00</td>
<td>220.00</td>
</tr>
<tr>
<td>8</td>
<td>DY5</td>
<td>321.10</td>
<td>12.00</td>
<td>219.50</td>
</tr>
</tbody>
</table>

Note: 1. Measured values, 2. Nominal values, 3. API5L GB steel.

The joints were fixed to the steel pedestals by bolting. The pedestals, in turn, were fixed to the strong concrete floor by means of mild steel (MS) bolts of 60 mm size. The entire assembly was placed under a reaction frame (Fig. 4.3). On the flange of the brace member, and between the horizontal cross beam of the reaction frame and the flange, 2000 kN hydraulic jack and proving ring were placed as shown in Fig. 4.3. The jack was connected to the electrically operated pumping unit by means of high pressure rubber hoses. A typical test set-up for the T joint is depicted in Fig. 4.3a. Test arrangement for the Y joint is illustrated in Fig. 4.3b. Axial brace compression loading was applied on the joints by means of the hydraulic jack. Load on the specimen was applied in equal increments.
Fig. 4.3 Typical Test Set-up for Axial Brace Compression Loading

a) T-Joint

(b) Y-Joint
Three dial gauges, reading to 0.01 mm, were mounted beneath the joint, one directly under the load point and the other two approximately at the third points, to facilitate recording of the deflection readings. For each load increment, deflection readings of all the three gauges were recorded. Load was monotonically increased till the ultimate load was reached.

The load-midspan deflection curves for fatigue damaged T joints are shown in Figs. 4.4 for joint DT2 and in Fig. 4.5 for joint DT3. In the case of Y joints, the load-midspan deflection curves are shown in Fig. 4.6 for joint DY2, Fig. 4.7 for joint DY3, Fig. 4.8 for joint DY4, and Fig. 4.9 for joint DY5. The experimental responses of the tested damaged joints, in general, display strain-hardening characteristics (Figs. 4.4 - 4.9).

It has been observed from the load-midspan deflection behaviours of the damaged joints that initial yielding occurs first at the cracked section. Loads corresponding to the initial yielding of the cracked section for all tested joints are given in Table 4.2. These values have been extracted from the appropriate load-deflection curves. The uncracked full cross section yielded later. Loads corresponding to the yielding of the full cross section are given in Table 4.2 for each tested joint. These loads were extracted from the respective load-deflection curves of the tested joints. The ultimate loads measured in the experimental investigation for different tested joints are given in Table 4.2. Some of the results obtained from this investigation have been published elsewhere (Thandavamoorthy et al 1997 c, d).

Joint DT1 alone was tested under axial brace tension loading using Instron servo-hydraulic dynamic testing system (Fig 4.10) to assess the residual strength of this cracked joint under tensile loading. As described above for compression loading, in this case also load was applied on the joint in increments. For each load increment, the midspan deflection
Fig. 4.4 Load-Midspan Deflection Curve for Damaged T Joint DT2
Fig. 4.5 Load-Midspan Deflection Curve for Damaged T Joint DT3
Fig. 4.6 Load-Midspan Deflection Curve for Damaged Y Joint DY2
Fig. 4.7 Load-Midspan Deflection Curve for Damaged Y Joint DY3
Fig. 4.8 Load-Midspan Deflection Curve for Damaged Y Joint DY4
Fig. 4.9 Load-Midspan Deflection Curve for Damaged Y Joint DY5
Fig. 4.10 Typical Test Set-up for Axial Brace Tension Loading
was measured by a dial gauge mounted underneath the chord member. It was observed during the test that the width of the crack started increasing at the load of 40 kN. At the load of 160 kN the crack started propagating along the circumference. At 400 kN, the brace was severed from the chord by fracturing of the weld. The experimental response of joint DT1 for the case of tension loading is shown in Fig. 4.11.

Table 4.2 Measured and Predicted Strengths of Damaged Stiffened Joints

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Specimen No.</th>
<th>Strength at yielding of cracked section (kN)</th>
<th>Strength at yielding of uncracked section (kN)</th>
<th>Ultimate strength of the joints (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Exptl.¹</td>
<td>Analytl.²</td>
<td>Exptl.¹</td>
</tr>
<tr>
<td>1</td>
<td>DT1</td>
<td>300.00</td>
<td>366.65</td>
<td>700.00</td>
</tr>
<tr>
<td>2</td>
<td>DT2</td>
<td>415.10</td>
<td>406.80</td>
<td>850.00</td>
</tr>
<tr>
<td>3</td>
<td>DT3</td>
<td>350.00</td>
<td>297.51</td>
<td>850.00</td>
</tr>
<tr>
<td>4</td>
<td>DY1</td>
<td>500.00</td>
<td>374.97</td>
<td>1040.00</td>
</tr>
<tr>
<td>5</td>
<td>DY2</td>
<td>330.00</td>
<td>395.18</td>
<td>750.00</td>
</tr>
<tr>
<td>6</td>
<td>DY3</td>
<td>415.10</td>
<td>334.92</td>
<td>740.00</td>
</tr>
<tr>
<td>7</td>
<td>DY4</td>
<td>415.10</td>
<td>345.48</td>
<td>1000.00</td>
</tr>
<tr>
<td>8</td>
<td>DY5</td>
<td>250.00</td>
<td>244.25</td>
<td>840.00</td>
</tr>
</tbody>
</table>

Note: ¹ - Not possible to load up to failure because of limitations in the test set-up as well as test specimens
² - Based on assumed values of yield and ultimate strength of steel
³ - Values extracted from the appropriate load-midspan deflection curves

4.2 DEVELOPMENT OF AN ANALYTICAL MODEL

An analytical model as described below was developed to assess the residual strengths of the internally ring stiffened fatigue damaged joints. As stated in section 4.1 above, the experimental responses of the typical tested fatigue damaged stiffened joints (Figs. 4.4 - 4.9) clearly exhibit the strain hardening characteristics. The conventional linear elastic-perfectly plastic model, therefore, cannot be a suitable proposition for this type of behaviour. Hence the strain hardening property was taken into
consideration in modelling the joint. According to the proposed model, linear elastic behaviour upto the yield was assumed. After yielding, linear strain hardening behaviour upto the ultimate strength was considered. This model is illustrated in Fig. 4.12. The strain energy, represented by the area under the stress-strain curve of the proposed model (Fig. 4.12), was computed. This was compared with the work done of the joint, represented by the area under the load-deflection curve of a T joint (Fig. 4.4). Both values were found to be equal.

As stated earlier, it was observed that the cracked section yielded first. Then a redistribution of loads took place. As a result of this, the uncracked full cross section at midspan yielded next. After this, strain hardening occurred and the behaviour became non-linear as is evident from Fig. 4.4. In consonance with this observation, it was assumed that the extreme fibre on the compression side of the cracked section yielded first. These joints had already been subjected to tensile fatigue loading. As a consequence of this loading, joints had been cracked. Therefore there is a possibility that the yield strength of the steel at the tip of the crack would have increased beyond the yield strength of 240 MPa. Therefore, a higher value of the yield strength depending on the extent of cracking, was assumed in the assessment of the residual strengths of the damaged joints. Considering the model proposed above, necessary equations for the determination of the moment capacity of the fatigue damaged internally ring stiffened tubular joints were derived from first principles. Details of the analytical procedure are given in the following sections.

4.2.1 Cracked section strength

As the joints had developed circumferential and through-thickness cracks, the area of the cross section of the joint has been reduced to some extent. The resulting effective section is shown in Fig. 4.13. The mean radius of the tubular cross section is R and its wall thickness is t.
Fig. 4.11 Load-Midspan Deflection Curve for Damaged T Joint under Tension Loading

Fig. 4.12 Proposed Analytical Model
Fig. 4.13 Strain and Stress Distributions of a Cracked Section
to cracking, the cross section has become unsymmetrical. So the C.G. of the section has been shifted downwards from its original position by a distance $e_d$ as shown in Fig. 4.13.

The strain and stress distributions across the cracked section are shown in Fig. 4.13. In arriving at these distributions the position of the neutral axis was assumed to be at a distance $e_d$ from the centre of the circle. The stress distribution is linear because of initial yielding. For this particular stress distribution, forces in various segments were computed.

From the measured length of the circumferential crack (Table 4.1), angle $\phi_1$ of segment 1 of zone I and angle $\phi_2$ of segment 2 of zone I were calculated. From the known values of these two angles $\phi_1$ and $\phi_2$ angles $\psi_{11}$ and $\psi_{12}$ in the respective quadrants corresponding to the compression area in zone I were determined. For a particular value of $e_d$ angle $\psi_2$ in zone II is given as

$$\psi_2 = \sin^{-1}\left(\frac{e_d}{R}\right)$$

(4.1)

From Eq. (4.1), angle $\delta$ in the respective quadrant is determined as

$$\delta = 90^\circ - \psi_2$$

(4.2)

For the derivation of the forces in different segments, an elemental area $da$ was considered at an angle $\alpha$ from the appropriate axis as shown in Fig. 4.13. The compressive force in segment 1 of zone I above the neutral axis is

$$F_{c11} = Rt \left\{ \sigma_{y11} \psi_{11} + \frac{(\sigma_{y11} - \sigma_{y11})}{\cos\phi_1} (1 - \sin\phi_1) \right\}$$

(4.3)

where
The compressive force in segment 2 of zone I above the neutral axis is
\[ F_{c12} = R t \left\{ \frac{(\sigma_y - \sigma_{y11})}{\cos \phi_2} (1 - \sin \phi_2) \right\} \] (4.6)

The compressive force in zone II is
\[ F_{c2} = \frac{2 R t \sigma_{y11}}{\sin \psi_2} \left( \psi_2 \sin \psi_2 + \cos \psi_2 - 1 \right) \] (4.7)

The total compressive force of the section is determined by adding all the above individual compressive forces given in Eq (4.3), Eq. (4.6) and Eq. (4.7)
\[ F_c = F_{c11} + F_{c12} + F_{c2} \] (4.8)

The moment of resistance of the cracked section was derived by taking moments of all the above forces about the neutral axis. The moment of the compressive force in segment 1 of zone I is expressed as
\[ M_{c11} = R^2 t \left\{ \sigma_{y11} \left[ 1 - \sin \phi_1 + \left( \frac{e_d}{R} \right) \psi_1 \right] + \frac{1}{4} \left( \sigma_y - \sigma_{y11} \right) \right\} \] (4.10)

The moment of the compressive force in segment 2 of zone I is
The moment of the compressive force in zone II is

$$M_{c2} = \frac{2R^2 t \alpha_{y11}}{\sin \psi_2} \left\{ \sin \psi_2 \left( \frac{e_d}{R} \psi_2 + \cos \psi_2 - 1 \right) + \left( \frac{e_d}{R} \right) \left( \cos \psi_2 - 1 \right) + \frac{1}{4} \left( 2 \psi_2 - \sin 2 \psi_2 \right) \right\}$$

The moment of the tensile force in zone III can be stated as

$$M_t = \frac{2R^2 t \alpha_{t}}{(1 - \cos \delta)} \left\{ \frac{1}{4} \left( 2 \delta - \sin 2 \delta \right) - \left( \frac{e_d}{R} \right) \left( \sin \delta - \delta \cos \delta \right) \right\}$$

The total moment of resistance of the cracked section is obtained by summing up of all the individual moments expressed in Eq. (4.10) through Eq. (4.13)

$$M = M_{c11} + M_{c12} + M_{c2} + M_t$$

When cracking is extensive and the angle $\phi_1$ in segment 1 of zone I is greater than 90°, the stress distribution is different from that shown in Fig. 4.13. The modified stress distribution for such a case is illustrated in Fig. 4.14. The area of the cross section corresponding to the compressive force in segment 1 of zone I is not available in this case. Therefore, Eq. (4.3) cannot be used. The compression area in zone II above the neutral axis is unsymmetrical and also gets modified as shown in Fig. 4.14 in contrast to that shown in Fig. 4.13 for the case of moderately cracked section. The equation for the compressive force in segment 1 of zone II is derived as

$$F_{c21} = \frac{R t \alpha_{y11}}{e_d} \left\{ \left( \frac{e_d}{R} \right) \psi_1 + \cos \psi_1 \psi_1 + \psi_2 - \cos \psi_1 \right\}$$

(4.15)
Fig. 4.14 Strain and Stress Distributions of an Extensively Cracked Section
The compressive force in segment 2 of zone II is obtained from Eq. (4.7) as

\[ F_{c22} = \frac{1}{2} F_{c2} \]  

(4.16)

The total compressive force for extensively cracked section is obtained by adding all the relevant individual compressive forces expressed in Eq. (4.6), Eq. (4.15) and Eq. (4.16)

\[ F_c = F_{c12} + F_{c21} + F_{c22} \]  

(4.17)

The moment of the compressive force in segment 1 of zone II is

\[ M_{c21} = \frac{R^2 \tau_{y1}}{e_d \sin \psi_{11}} \left\{ \frac{e_{d1}^2}{R} \psi_{12} + 2 \frac{e_{d1}}{R} \left( \cos \psi_{11} + \psi_{21} - \cos \psi_{11} \right) + \frac{1}{4} \left( 2 \psi_{21} - \sin^2 \psi_{11} + \psi_{21} - \sin^2 \psi_{11} \right) \right\} \]  

(4.18)

The moment of the compressive force in segment 2 of zone II is obtained from Eq. (4.12) and is given as

\[ M_{c22} = \frac{1}{4} M_{c2} \]  

(4.19)

The moment of resistance of the extensively cracked section, with the absence of compression area in segment 1 of zone I and with the reduced area of segment 1 of zone II, is derived by adding all the individual moments given in Eq. (4.11), Eq. (4.13), Eq. (4.18) and Eq. (4.19)

\[ M = M_{c12} + M_{c21} + M_{c22} + M_t \]  

(4.20)

The computation of the compressive and tensile forces depends on the position of the neutral axis at a depth \( e_d \) below the centre of the circle, which itself is unknown and has to be determined by equilibrium of forces. The calculations are laborious and involve iteration too. Therefore, a computer programme in FORTRAN language was developed for the computation of the forces. With an assumed initial value of \( e_d \), compressive and tensile forces were calculated. The total compressive force was equated to the tensile force. Equilibrium was checked. If equilibrium was
not satisfied, then the calculations were repeated with another value of \( e_d \). The iteration was terminated when the compression and tension were equal and the force equilibrium was achieved. The value of \( e_d \), which satisfied the force equilibrium condition, was used to compute the moments. All the individual moments were added up to arrive at the final moment of resistance of the cracked section. Manual calculations were also performed to check the computer results.

4.2.2 Strength of uncracked section at yielding

The strain and stress distributions for an uncracked section is shown in Fig. 4.15. As the cross section is symmetrical, the C.G. lies at the centre of the circle. In this case, areas of the compression and tension are equal and hence the forces are in equilibrium, because the stresses are also equal. Therefore, moments of forces about the C.G. are calculated directly. An elemental area \( da \) of at angle \( \alpha \) about the vertical axis is considered for the derivation of the moments (Fig. 4.15). The moment of resistance of the full section at initial yielding is

\[
M = \pi R^2 \sigma_y \tag{4.21}
\]

4.2.3 Strength of uncracked section with strain hardening effect

The strain and stress distributions for the ultimate strength of the full section in a cracked joint, considering the strain hardening effect, are shown in Fig. 4.16. The moments of the different forces about the C.G. are taken as the section is symmetrical and the stresses are equal. The moment of forces in zone I is given as

\[
M_i = 4R^2t \left\{ \sigma_y \sin \phi_0 + \frac{1}{4} \left( \frac{\sigma_u - \sigma_y}{1 - \cos \phi_0} \right) (2\phi_0 - \sin 2\phi_0) \right\} \tag{4.22}
\]
Fig. 4.15 Strain and Stress Distributions of an Uncracked Section at Initial Yielding

Fig. 4.16 Strain and Stress Distributions of an Uncracked Section at Ultimate Load
The moment of forces in zone II is given as

\[ M_{II} = R \sigma_y \left( \frac{2\psi_0 - \sin2\psi_0}{\sin\psi_0} \right) \]  \hspace{1cm} (4.23)

The moment of resistance of the uncracked section considering the strain hardening effect is got by adding Eq. (4.22) and Eq. (4.23) and expressed as

\[ M = M_I + M_{II} \] \hspace{1cm} (4.24)

The computation of the moment capacity of the uncracked section based on the derivations given in sections 4.2.2 and 4.2.3 above were also included in the computer programme described in section 4.2.1 above. The computer programme developed for the complete analysis is presented in Appendix 1.

4.3 NUMERICAL INVESTIGATIONS

Finite element analysis using NISA II Software Package was performed to predict the behaviour of the internally ring stiffened fatigue damaged joints. For the purposes of the analysis, the chord and brace members of the joint were discretized using 2-D prismatic beam elements (NKTP = 1, NORDER = 1) with 2 nodes for each element and 3 degrees of freedom per node (Kothawala 1991). The chord members of T (Fig. 4.17a) and Y (Fig. 4.17b) joints were divided into 21 elements. The brace was taken as a single element in both cases. Simply supported boundary conditions were assumed at the ends of the chord. Top of the brace was assumed to displace downward only and to rotate about the axis perpendicular to the plane of the brace. It was restrained from moving in the perpendicular plane. Area and moment of inertia of cross sections of the chord and brace members were computed from their given dimensions and they formed inputs for the computer analysis. The moment of inertia of the effective cross section at the cracked location was computed about its own C.G. This value was given as input for the computer analysis. The Young's Modulus, E, was taken as $2 \times 10^5$ MPa.
Fig. 4.17 FE Model of Damaged Stiffened Joints

(a) T-joint

(b) Y-joint
Compressive load was applied on top of the brace along its axis. Load was applied in stages. For each stage of the applied load, linear static analysis was carried out using NISA II package and the value of the deflection at mid-span was obtained. This procedure was continued till the cracked section yielded. After this stage, a reduced modulus of $6.0 \times 10^4$ MPa was given as input for the cracked element alone because the rigidity of the section has been reduced due to cracking. This was based on the analytical model described in section 4.2. As before, with this modified value of the modulus the analysis was carried out till initial yielding of the uncracked section occurred.

For the strain hardening zone, the value of the modulus was taken equal to $6.00 \times 10^4$ MPa. For this reduced modulus, the deflection value corresponding to a particular load stage was determined by iterative technique. In this process, it was assumed that yielding in the elements commenced from the centre of the chord, as this is the highly stressed region. It then progressed gradually on either side of it. This analysis was continued till the ultimate load was reached.

Typical responses obtained from the numerical analysis of the tested joints are shown in Figs. 4.4 and 4.5 for T joints and in Fig. 4.6 for Y joint. It was observed that the experimental and predicted load-midspan deflection behaviours were in close agreement.

4.4 RESULTS AND DISCUSSION

It was observed in the case of all tested internally ring stiffened fatigue damaged T joints that the predominant mode of deformation was bending of the chord member along its longitudinal axis. Absolutely no ovaling and consequent punching of chord occurred in the vicinity of the welded intersection. As stated in Chapter 3, due to the deformation of the
chord wall unstiffened joints are normally associated with its ovaling in the vicinity of the welded intersection. The final failure usually occurs due to punching shear.

The distinct advantage of the ring stiffened tubular joint is clearly visible in this experimental investigation. When the cracked section was yielded, a redistribution of load occurred and the uncracked section was able to carry on the load till the ultimate stage. This could be possible only because of the flexural bending of the chord member. This could not have been possible in the case of unstiffened joint that normally would have failed by ovaling and punching. Therefore it could not have taken additional load because local punching and ovaling of the chord wall cannot transfer load to the adjoining intact sections. Therefore, employment of the internally ring stiffened tubular joints in the construction of offshore structures has the great advantage. They have an in-built load transfer mechanism in case damaged by fatigue loading.

Considering the analytical model developed in Section 4.2 above, loads were computed for all tested damaged joints. Loads corresponding to yielding of the cracked section are given in Table 4.2. Similarly calculated loads at yielding and at ultimate stage of the uncracked section are also given in Table 4.2. In all these cases, loads were calculated by considering the nominal values of thicknesses of chord and brace members. In these calculations yield strength of steel, stated in section 4.1 above, was assumed. The predicted loads corresponding to the yielding of both cracked and uncracked sections were in reasonable agreement with the experimental values.

In the case of joint DT1, it was not possible to go upto the ultimate load because the loading system had a limited capacity. Welding of the stiffeners in the supporting bracket of the experimental set-up cracked during testing of joint DY2 near ultimate load. Therefore test was terminated.
at the load of 1677.30 kN. Since the brace member of the joint DY3 was slightly tilted, load could not be continued beyond 1600 kN. During testing of the joint DY4, the crack widened and at the cracked section one part of the chord wall in the compression side pierced through the other part telescopically near ultimate load. Therefore, test was terminated at a load of 1759.10 kN.

Considering the model proposed in section 4.2 above, theoretical ultimate loads of the damaged joints were calculated and are given in Table 4.2. These loads were computed by considering the nominal values of thicknesses of chord and brace members. As for the yield and ultimate strengths were concerned values stated in section 4.1 were adopted for the calculation of the analytical loads. On the whole, the predicted ultimate loads are in good agreement with the measured values. Therefore, the proposed bi-linear stress-strain model with the slope of the second linear portion as 0.3E can be used to assess rationally the residual strengths of fatigue damaged internally ring stiffened T and Y joints. This may be of great help in taking a rational decision on repairing the damaged offshore structures.

Assessment of the strength of damaged stiffened tubular joints has not been addressed in the currently available design codes. Therefore the bi-linear model proposed in this investigation can be incorporated in these codes as design guidelines for the evaluation of the damaged condition. The reason for this that this model has been validated with experimental results and also no such model is available at present.

It was observed during the tests that in the case of joints DT2 and DY1 stiffeners had been welded away from the brace face. Therefore the chord wall between the stiffener and the brace face deflected near ultimate load. This has affected the load carrying capacity of these joints to some extent. However, no ovaling of chord member occurred. This brings
out to the fore the importance of tolerances and accuracy in welding. Fabrication defects may defeat the purpose for which the stiffeners have been welded to the chord wall.

In the case of all tested internally ring stiffened Y joint also bending of the chord member was observed to be the dominant mode of deformation just similar to that of the T joints. No ovaling or punching was observed in this case too.

A comparison of typical responses of an undamaged and a fatigue damaged internally ring stiffened tubular T joint has been made in Fig. 4.18. The degradation in stiffness of the damaged tubular is quite substantial when it is compared with the original stiffness of the undamaged joint of the same configuration and dimensions. The load corresponding to the initial yielding of the full section of the cracked joint has been reduced to a greater extent. For instance, from a load of 1070 kN for an undamaged joint it has been reduced to 800 kN in the case of the damaged joint. After this load of 800 kN the damaged joint had undergone a larger deflection than the undamaged joint. This is due to cracking and consequent reduction in stiffness of the joint.

Typical experimental responses of the fatigue damaged T and Y joints were compared in Fig. 4.19. Initially the responses were the same for both upto the yielding of the uncracked section. After this stage, the T joint had undergone a larger deflection than the Y joint though it had lesser degree of cracking than the Y joint. The reason for this is that the Y joint was tested at an inclination of 30° (Fig. 4.3b) to the horizontal, and the deflection along the loading direction is less than that along the normal. Though T and Y joints are of the same dimensions, because of its orientation the Y joint is stiffer than the T joint.
Fig. 4.18 Load-Deflection Relations of Undamaged and Damaged Joints - Typical Comparison
Fig. 4.19 Comparison of Load-Deflection Relations of Fatigue Damaged T and Y Joints
In the case of joint DT1, which was also tested under axial brace tension loading, the initial yielding of the cracked section occurred at 62.5 kN. The uncracked section yielded at 220 kN. The measured ultimate strength of the joint under tension loading was 400 kN. In this type of loading the circumferential crack was positioned on the tension side. The area of cross section available for the tensile force is also very small. Therefore there was a drastic reduction in the strength of the joint. Even in axial brace tension loading also, as observed in the case of joint DT1, the predominant deformation of the internally ring stiffened joint was bending only. No ovaling of the chord wall was observed in this case also.

There has not been a substantial reduction in the ultimate strength of the fatigue damaged internally ring stiffened joints under axial brace compression loading when compared to the strength of the undamaged joints. However, the reduction in strength of the damaged joints under axial brace tension loading is quite substantial. This is quite evident from the testing of the joint DT1 in tension loading. The capacity of the cracked joint under tension loading is less than one-fourth the capacity of the undamaged joints of the same dimensions under compression loading. Wave loading falls in the category of reversal of loading. The tensile nature of the loading may seriously impair the strength of the structure and jeopardize its integrity if such cracked joints were present in the structure.

Once the offshore structure is damaged under fatigue loading, in addition to the strength, other detrimental effects that endanger the integrity of the structure are also to be considered. From this point of view, the sea water may penetrate through the cracks and fill the inside of the member. This may set in corrosion of the tubular member from the inside, which portion is not at all accessible for inspection.

The degradation of the stiffness of the damaged joint may lead to large deflection of the structure under loading and perhaps beyond
permissible limits too. This may seriously hamper various other functions also. The reduction in stiffness of the damaged joint may contribute to the reduction in the fundamental frequency of the structure. This may lead to the resonance of the structure. The amplitude of the vibration of the structure under wave excitation may also increase due to this phenomenon.