Methods for Increasing the Fatigue Life of Repaired Welded Joints of Offshore Oil and Gas Facilities

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Abstract. As a result of the investigation of the resource of the repaired welded joints it was found that it is much lower than that of the new joint and in some cases may not correspond to the required extension period. In connection with this, the authors proposed the use of reinforcing tee structures and justified the parameters.

1. Introduction
Offshore oil and gas facilities subjected to various forces, which causes periodically variable cyclic stresses. The action of these stresses leads to the accumulation of fatigue damage, followed by the destruction of welded joints. Based on experimental research, the life of the repaired welded joint is significantly shorter in compare with new one. As a result, in some cases repaired welded joint cannot meet requirements related on life extension period.

2. The reinforced clamp
The value of the predicted endurance depends on the values of the variables acting in the repaired welded joints (RWJ). According to Starokon I V, it is possible to increase the service life of the repaired welded joint by reducing the acting alternating stresses. Based on the fatigue curves [2], which obtained as a result of the experimental research with "T"-type connection*, it was found the dependency between acting stress amplitude reduction and endurance of repaired welded joint for different time periods. (*T-type connection means the connection between vertical element (Nominal diameter) DN=700mm, (wall thickness) WT=20mm) and horizontal element (DN=400mm, WT=12mm). Kogaev V P endurance calculation methodology used as a basis for considered calculations. [1].
Table 1. Dependence between alternating stress amplitudes and endurance of welded joints.

| Wave height, h | The amplitude of the alternating stress, $\sigma_a$ | Reduction of the amplitude of alternating stresses by 1.2 times | Reduction of the amplitude of alternating stresses by 1.5 times | Reduction of the amplitude of alternating stresses by 1.6 times | Reduction of the amplitude of alternating stresses by 1.7 times |
|---------------|-----------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 11.2          | 41                                           | 34.2                                            | 27.3                                            | 25.6                                            | 24.1                                            |
| 9             | 30                                           | 25.0                                            | 20.0                                            | 18.8                                            | 17.6                                            |
| 7             | 20                                           | 16.7                                            | 13.3                                            | 12.5                                            | 11.8                                            |
| 5.5           | 16                                           | 13.3                                            | 10.7                                            | 10.0                                            | 9.4                                             |
| 4.5           | 12                                           | 10.0                                            | 8.0                                             | 7.5                                             | 7.1                                             |
| Endurance, years | 6.9                                           | 13                                               | 23                                               | 39                                               | 49                                               |

The calculations carried out by Starokon I V, Golovachev A O and Nadyrov R I in the SolidWorks software showed that the stresses amplitudes reduction in 1,2 times leads to RWJ endurance increasing up to 13 years, moreover the stresses amplitudes reduction in 1,5 times leads to RWJ endurance increasing up to 23 years. The reduction the alternating stress amplitudes could be achieved in several ways. One of them is installation of the reinforced clamps on the T-joint, shown in figures 1-4 (RC-T).

![Figure 1](profile_view_RC-T.png)  ![Figure 2](isometric_view_RC-T.png)

**Figure 1.** Profile view RC-T.  **Figure 2.** Isometric view RC-T.

![Figure 3](sketch_RC-T.png)  ![Figure 4](disassembled_RC-T.png)

**Figure 3.** Sketch RC-T.  **Figure 4.** RC-T in disassembled state.

The best practice in the piping manufacturing industry is method of forming T-structures from two parts (upper and lower ones) with a diameter up to DN=1400 with post subsequent welding and
cutting. This technology could be applied to the manufacture of RC-T and assuming the following sequence of operations: cutting of the workpiece from the steel plate, heating the workpieces and subsequent stamping of the upper and lower parts. To connect the branch to the main part of the T-structure, the hole is cut with subsequent flanging on the stamp. Then the parts should be welded together, post-weld heat-treated, machined and inspected.

Let analyze various parameters of such clamps and select the most effective solution. The considered parameters are the efficiency of stress reduction, wall thickness, length of pipes (branches), radius of rounding, connection tightness, complexity of manufacture and installation. The main parameters of RC-T shown in figure 3.

Let consider the welded joint, which located on structure of fixed jacket type offshore platform. This connection consist of a vertical column (DN=700mm, WT=20mm) and a horizontal element (DN=400mm WT=12mm). The stress $\sigma$ acts in considered joint. Based on software simulation, the changes of the stresses state of the joint weld ($\sigma$) with installed RC, which had different parameters, the efficiency coefficient of stress reduction ($K_{урк}$) was determined:

$$K_{урк} = \frac{\sigma_f}{\sigma_{ном}}$$

where: $\sigma_f$ and $\sigma_{ном}$ - the actual and nominal stresses acting in the welded joint.

Real structural elements of the fixed offshore platform have significant corrosion damage due to harsh environment, which prevents the tightening of the RC-T surface and the surface of structure elements.

The bad tightening lead to spotted load distribution and creating local stress concentration areas. To mitigate such effect, the connection area surface should be increased. Authors conducted the SolidWorks stress simulation of welded joint with RC and without it. The results of simulation shown on figures 5, 6.

![Figure 5. Stresses distribution without RC-T.](image1)

![Figure 6. Stresses distribution with RC-T.](image2)
Table 2. Stress reduction efficiency coefficient on the example of the RC-T (DN=700 (main pipe), DN=400mm (horizontal element)).

| The length of the branches | Wall thickness of the main pipe RC-T and branch, mm | Radius of rounding RC-T, mm |
|----------------------------|--------------------------------------------------|-----------------------------|
|                            | \( \delta_1 = 8; \delta_2 = 6 \)                | R20 | R30 | R40 | R20 | R30 | R40 | R20 | R30 | R40 |
| 2 (d1, d2)                 | 1.85                                           | 2.17 | 2.3 | 1.65 | 1.88 | 2.1 | 1.46 | 1.72 | 1.84 |
| 1.5 (d1, d2)               | 1.85                                           | 2.17 | 2.3 | 1.65 | 1.88 | 2.1 | 1.46 | 1.72 | 1.84 |
| 1 (d1, d2)                 | 1.78                                           | 2.10 | 2.26 | 1.59 | 1.83 | 2.06 | 1.44 | 1.66 | 1.81 |
| 0.75 (d1, d2)              | 1.70                                           | 2.03 | 2.21 | 1.54 | 1.79 | 2.02 | 1.42 | 1.61 | 1.79 |
| 0.5 (d1, d2)               | 1.63                                           | 1.96 | 2.17 | 1.48 | 1.74 | 1.98 | 1.4 | 1.55 | 1.76 |

| The length of the branches | Wall thickness of the main pipe RC-T and branch, mm | Radius of rounding RC-T, mm |
|----------------------------|--------------------------------------------------|-----------------------------|
|                            | \( \delta_1 = 20; \delta_2 = 12 \)              | R20 | R30 | R40 | R20 | R30 | R40 | R20 | R30 | R40 |
| 2 (d1, d2)                 | 3.5                                             | 3.7 | 3.7 | 2.5 | 2.8 | 2.8 | 2.2 | 2.3 | 2.4 |
| 1.5 (d1, d2)               | 3.5                                             | 3.6 | 3.7 | 2.5 | 2.7 | 2.8 | 2.1 | 2.3 | 2.4 |
| 1 (d1, d2)                 | 3.4                                             | 3.5 | 3.7 | 2.4 | 2.6 | 2.7 | 2.1 | 2.2 | 2.3 |
| 0.75 (d1, d2)              | 3.3                                             | 3.3 | 3.4 | 2.3 | 2.6 | 2.6 | 2.0 | 2.2 | 2.3 |
| 0.5 (d1, d2)               | 3.0                                             | 3.1 | 3.1 | 2.1 | 2.3 | 2.4 | 1.9 | 2.1 | 2.2 |

The similar results were obtained by modelling RC-T for the welded joint (column: DN=1000 mm, WT=20mm; horizontal element: DN=500mm, WT=15mm).

Table 3. Stress reduction efficiency coefficient (RC-T, DN=1000x500 mm).

| The length of the branches | Wall thickness of the main pipe RC-T and branch, mm | Radius of rounding RC-T, mm |
|----------------------------|--------------------------------------------------|-----------------------------|
|                            | \( \delta_1 = 20; \delta_2 = 15 \)              | R20 | R30 | R40 | R20 | R30 | R40 | R20 | R30 | R40 |
| 2 (d1, d2)                 | 3.5                                             | 3.6 | 3.8 | 2.5 | 2.9 | 3.0 | 2.1 | 2.1 | 2.3 |
| 1.5 (d1, d2)               | 3.5                                             | 3.6 | 3.8 | 2.5 | 2.9 | 2.9 | 2.1 | 2.1 | 2.3 |
| 1 (d1, d2)                 | 3.4                                             | 3.6 | 3.7 | 2.4 | 2.7 | 2.9 | 2.0 | 2.1 | 2.3 |
| 0.75 (d1, d2)              | 3.3                                             | 3.5 | 3.6 | 2.4 | 2.6 | 2.8 | 2.0 | 2.0 | 2.2 |
| 0.5 (d1, d2)               | 3.1                                             | 3.2 | 3.4 | 2.3 | 2.6 | 2.6 | 1.9 | 2.0 | 2.1 |

The calculations showed that the branch length increasing leads to stress reduction from 9% to 19% (and continues to decrease it with further extension of the branches), but a significant such length increasing provides additional weight increasing. This way is not significantly reduce the acting RC-T stresses.

The radius of rounding increasing leads to stress reduction from 3% to 15% (and continues to decrease with increasing radius of rounding), but also this is not effectively reduce the amplitude of the alternating stresses.
The greatest stress state decrease from 45% to 65% is achieved by increasing the wall thickness.

3. The functional-cost analysis coefficients for RC-T

To select the most effective design, FCA method (functional-cost analysis) was applied. This methodology is used for optimal configuration selection in CAD (computer-aided design) and is best practice in optimization area.

According to this method, all parameters should be divided into mandatory (categories A), auxiliary (categories B) and excessive (categories C). The method itself involves the analysis of the design and determining the optimal ratio of the parameters in terms of production and installation costs. One of the most important parameter that contribute the selection of the optimal design is metal consumption. It is obvious that the higher the metal consumption, the more complicated installation process of RC-T, the complexity of manufacturing increases the cost of the clamp itself and also heavy weight of clamp create significant loads on the structure elements. Metal consumption should be defined as the total weight of RC-T.

Table 4. Weight of RC-T (different configurations).

| The length of the branches | Wall thickness of the main pipe RC-T and branch, mm | Weight, kg |
|----------------------------|-----------------------------------------------|------------|
|                            | $\delta_1=8; \delta_2=6$                     | $\delta_1=6; \delta_2=4$ | $\delta_1=4; \delta_2=2$ |
| 2D                         | 438,7                                         | 323,4      | 209 |
| 1,5D                       | 321,5                                         | 237        | 153 |
| 1D                         | 204,4                                         | 150,6      | 97  |
| 0,75D                      | 146                                           | 107        | 69  |
| 0,5D                       | 87                                            | 64         | 41  |

| The length of the branches | Wall thickness of the main pipe RC-T and branch, mm | Weight, kg |
|----------------------------|-----------------------------------------------|------------|
|                            | $\delta_1=20; \delta_2=12$                  | $\delta_1=13; \delta_2=8$ | $\delta_1=10; \delta_2=8$ |
| 2D                         | 1082,8                                        | 700        | 554,5 |
| 1,5D                       | 792,2                                         | 512,3      | 406,5 |
| 1D                         | 501,1                                         | 324,6      | 258,5 |
| 0,75D                      | 356,3                                         | 231        | 184,5 |
| 0,5D                       | 211                                           | 137        | 110,5 |

Let consider the process of selection the parameters RC-T, based on repaired welded joint (DN=700x400 mm), which service life should be increased up to 23 years after repair. Based on calculations (table 1), the amplitudes of alternating stresses should be reduced by 1.5 times. All variants of RC-T, which are not able to reduce the amplitudes of alternating stresses, at least in 1.5 times, should be eliminated.
Table 5. The functional-cost analysis coefficients for RC-T.

| The length of the branches | Wall thickness of the main pipe RC-T and branch, mm | Radius of rounding RC-T, mm |
|---------------------------|-----------------------------------------------|--------------------------|
| L1,L2                     | δ₁= 8; δ₂=6                                    | δ₁=6; δ₂=4               | δ₁=4; δ₂=2 |
| 2 (d₁, d₂)                | 0.006 0.007 0.007 0.007 0.007 0.008 0.009 - | 0.011 0.011 - 0.017 0.019 - | 0.023 0.026 - |
| 1.5 (d₁, d₂)              | 0.004 0.005 0.005 0.005 0.006 0.006 - - -    | 0.008 0.009 - - - - - -   | - - - - - - |
| 1 (d₁, d₂)                | 0.009 0.010 0.011 0.011 0.012 0.014 - - -    | - - - - - - - - - - - -   | 0.017 0.019 - |
| 0.75 (d₁, d₂)             | 0.012 0.014 0.015 0.014 0.017 0.019 - - -    | - - - - - - - - - - - -   | 0.023 0.026 - |
| 0.5 (d₁, d₂)              | 0.019 0.023 0.025 0.023 0.027 0.031 - - -    | - - - - - - - - - - - -   | 0.038 0.043 - |

4. Conclusion

The increasing of the wall thickness, Radius of rounding with the branch length decreasing is the most preferable way to reduce stresses with minimum metal consumption.

The highest value of FCA coefficient is equal to 0.043. In this case, the RC-T has wall thickness 4mm (main pipe) and 2mm (branch), the length of both elements is equal to 0.5 of the each element diameter.

5. References

[1] Kogaev V P, Makhutov I A and Gusenkov A P 1985 Calculations of machine parts and structures for strength and durability Machine Building Moscow 224 p

[2] Starokon I V 2016 Results of experimental and analytical study of the service life of repaired welded joints of offshore oil and gas facilities Construction of oil and gas wells on land and at sea 12 (ISSN 0130-3872) 25-28 p