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Fatigue tests of damaged tubes under flexural loading

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Abstract. Despite the proliferation of the industrial application of steel tubes, the effect of collision on the surface of steel tubes subject to cyclic loading has largely remained untouched. This paper studies the fatigue behavior of steel tubes which are impacted by an external object. A dent imperfection caused by a collision was modeled and fatigue tests were conducted using a MTS machine. Fatigue life as well as the failure modes were thoroughly discussed in a way that the fatigue life of the dented tubes with similar geometrical specifications at full-scale can be generalized.

Keywords: thin tubes; fatigue life; dent and collision; failure mode

1. Introduction

Steel tubes are extensively used as structural members in civil and mechanical engineering structures. Cyclic loading may expose these elements to fatigue failure in many industrial applications. On the other hand, these structures are often unprotected against external collisions during their service life. This issue motivated the authors to investigate the possible adverse effect of damage on the fatigue life of these structures under in-plane bending. Two different instances of the application of these tubular members are presented in Figs. 1 and 2 in which cyclic bending caused by wind loading can make such structures vulnerable to fatigue failure.

Some references regarding the static bending stability of the tubes can be found which show buckling and failure modes of these structures under flexural stresses. Most recently bending stability of circular thin-walled sections was investigated and the buckling mode on the compression side was observed (Limam *et al*. 2010, Ghanbari Ghazijahani and Showkati 2013a), (Ghazijahani and Showkati 2012) and (Corona *et al*. 2006). Fatigue behavior of the tubes, on the other hand, was studied and failure modes as well as the stress concentration were reported (Jiao *et al*. 2013), (Mashiri *et al*. 2004), (Mashiri *et al*. 2002a, b), (Wang *et al*. 2011) and (Chang *et al*. 2005, Chen *et al*. 2013, Park *et al*. 2012). Furthermore, some investigations reported various damaged structures under different kinds of loadings such as (Ghazijahani and Showkati 2013b, Ghanbari Ghazijahani *et al*. 2014a, b, c). It should be noted that the most relevant investigation to the present study were reported on the dented tubes under static bending (Limam *et al*. 2012).

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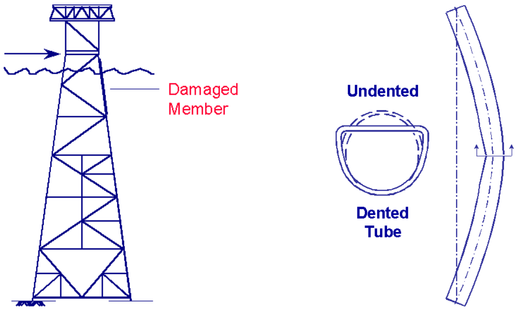


Fig. 1 Tubular members in an offshore platform (see the references)

Fig. 2 Tubular members in overhead traffic signs

There is no study considering the damaged tubes under cyclic loading. Therefore this study intends to fill the gap of impacted tubes exposed to fatigue loading. The key objective of this study is to determine the effect of the dent imperfection on the failure mode and, more importantly the fatigue life of such structures.

2. Experimentation

2.1 Test set-up

MTS machine, specimens and indentation

Fatigue tests were conducted by a MTS-810 machine. This machine was calibrated before the tests to ensure the accuracy of results in accordance with Australian Calibrating Services (ACS). The loading arm required for bending was created by mounting a box-section (Fig. 3). The specimens were bolted to the end plate with high-strength bolts. A shell segment was used at the loading point to provide a uniform surface for the bottom portion of the tubes.

Specimens of initially identical geometry were made of ERW mild steel circular hollow sections with D/t ratio of 47.6 (see Table 1) which are extensively used as structural elements. Before the welding of the specimens to the end plate, one end of the tubes was machined to ensure that it was perpendicular to the plate. A rotating welding machine was employed in order to achieve a high-quality welding (Fig. 4).

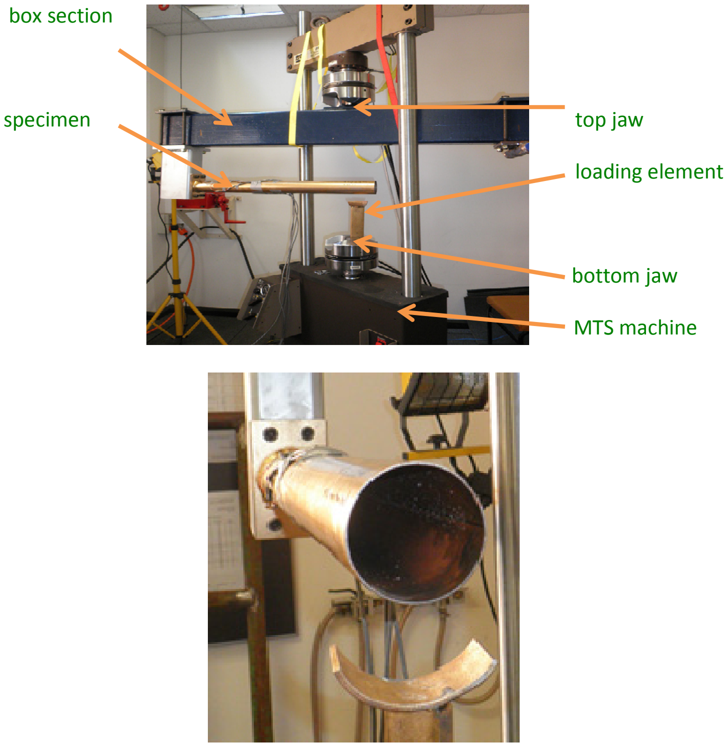


Fig. 3 Overall view of the test program and loading element

Table 1 Geometry of the tested specimens

Specimen label	*D* (mm)	Length (mm)	*D*/*t*
CLC.1 to 6	76.2	620	47.6

(a) (b)

Fig. 4 (a) The rotating machine for welding; (b) a welded specimen

A variety of damage to these six specimens was simulated by denting near the support on the compression loading side. To achieve an accurate and controllable dent, indentation conducted by a universal testing machine and an indenter (see Fig. 5). A LVDT was employed to measure the displacement of the indenter so that a designed indentation was created. A vernier was used to check the dent′s depth until the designed dent was achieved. Geometry of each dent is specified in Table 2, where parameters d, D_w and D_L are defined in Fig. 6. Typical geometry of centre-line of two dents and different dented specimens before testing are illustrated in Figs. 7 and 8.

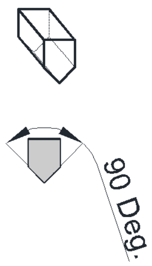


Fig. 5 Overall view of the indenter

Table 2 Geometry of the dented area

Specimen label	d (mm)	D_W (mm)	D_L (mm)
CLC.1	without dent	-	-
CLC.2	1.2	16	13
CLC.3	1.5	21	17
CLC.4	4.7	45.5	33.5
CLC.5	7.9	68.8	53
CLC.6	12.8	89.5	78.2

*Note: all dents were on the compression side, 50 mm from the fixed support end

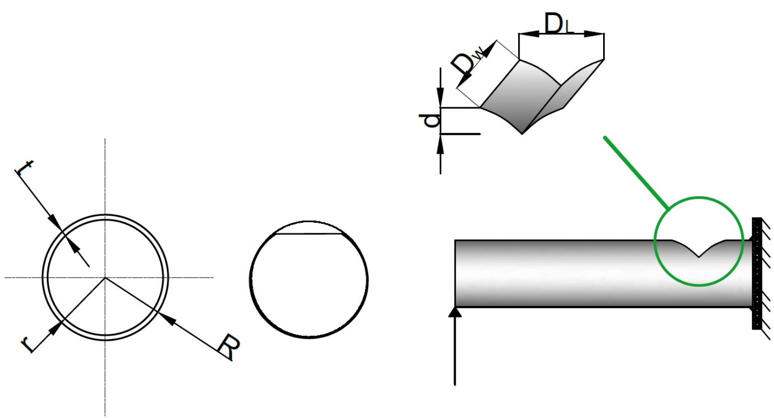


Fig. 6 Indentation illustration and schematic position of the dent ("r" is internal radius)

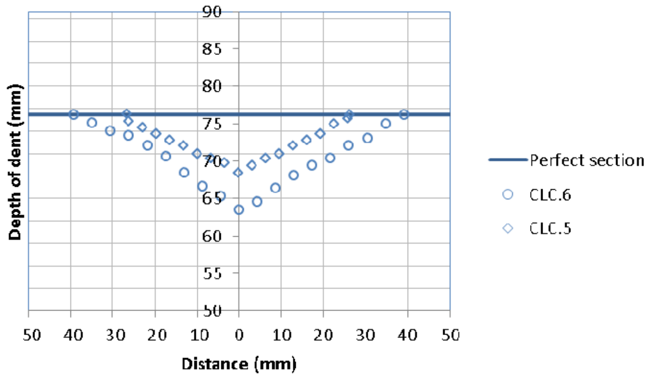


Fig. 7 Longitudinal centre-line of the dent for the specimens CLC.5 and CLC.6

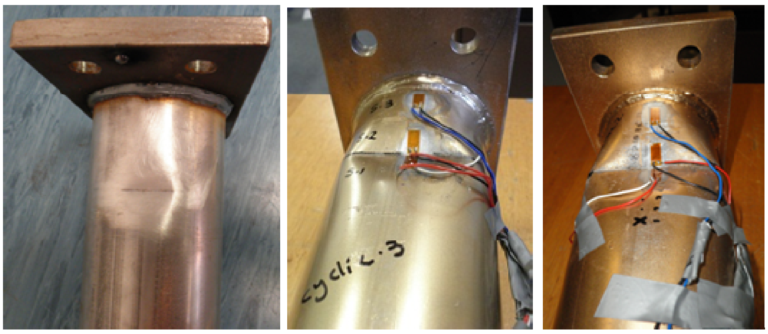


Fig. 8 Damages on different specimens (slight, medium and severe)

Measurements

CEA06240VZ120 strain gauges were employed to record the strain data at desired points. A LabVIEW data acquisition program was used in order to record data during the testing program. The displacement at the loading point was measured by the MTS machine. All the tests were conducted under load-control condition. A specimen was deemed as a failed sample when a crack had developed and the specimen was unable to carry the cyclic loading.

(a) (b) (c)

Fig. 9 Failure stages of the coupon specimen

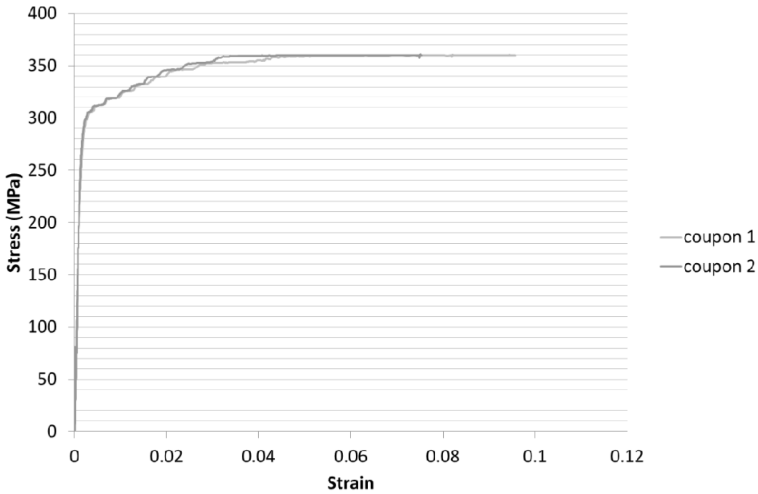


Fig. 10 Stress-strain curve of the material

2.2 Tensile test and material properties

Tensile coupon tests were conducted so as to determine the material properties of the current specimens. A yield stress of 307 MPa, ultimate tensile strength of 360.2 MPa and Young's modulus of 216.3 GPa were obtained respectively. The failure instant and the stress-strain curve of the coupon test are presented in Figs. 9 and 10. It is noted that a loading protocol of 2.8 kN and 0.28 kN was defined as maximum and minimum loads for each cycle.

3. Experimental observations and findings

3.1 Failure modes and general observations

Overall, three different failure modes were observed from this experimental program. It should be mentioned that, although the dented region was on the compression side, the fatigue crack happened at the dent itself for the specimens with medium and severe dents.

BTS mode of failure

This mode of failure is called brace-tension-side mode of failure (Jiao *et al*. 2013) and occurred at the weld-toe on the tension side of the tube specimens (Fig. 11). This mode of failure was observed in the intact specimen (CLC.1) as expected as well as in the specimens with relatively small rate of *d*. This suggests that minor damage on the compression side of the members does not affect the fatigue life of the specimens which is largely dependent on maximum tensile stresses. Note that the crack occurred just beside the weld where the maximum tension stress would be.

DWF mode of failure

This mode of failure occurred for the specimens with a medium rate of dent severity. Since cracks occurred both in the dented zone and near the welding on the tension side, hereafter, it is

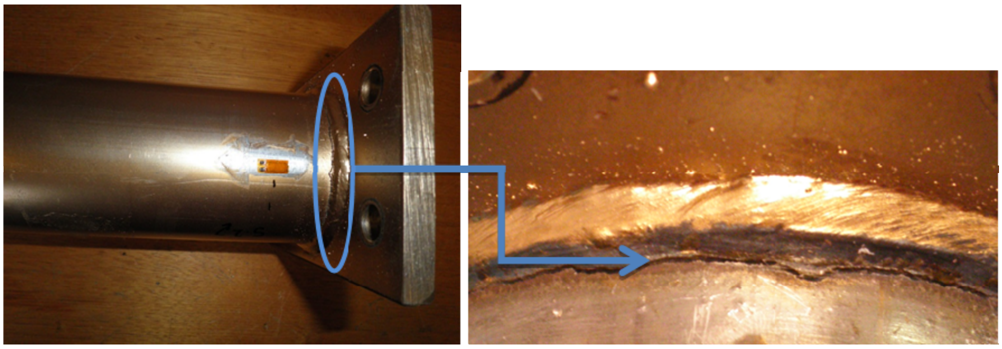


Fig. 11 BTS failure mode of the intact specimen (CLC.1)

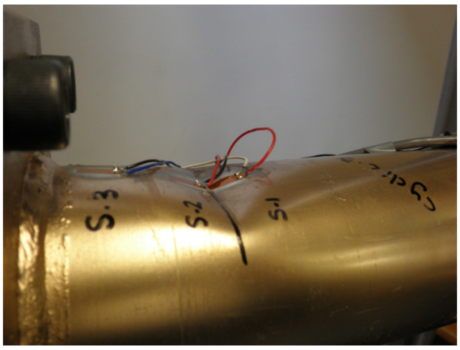


Fig. 12 CLC.5 specimen before the testing

(a) (b)

Fig. 13 (a) Fatigue crack at the edge of the dent for CLC.5; (b) tension crack at the bottom of CLC.5

called DWF. For this mode of the failure two cracks were initiated at both ends of the dented area followed by a third crack which developed at the tension side of the weld-toe (see Figs. 12 and 13). Accordingly, two areas of the specimen were affected by the fatigue crack. It is noteworthy that there was an interesting movement of the dented area under cyclic loading such that the dented area moved towards the inside of the tubes when the specimen was loaded and recovered when the loading was released. With the cyclic load frequency of 3 Hz this mode was fairly similar to the beating of a heart with a regular rhythm. Thus, the pre-failure phase of the specimens was referred to as *Heartbeat Mode* to provide an insight into the deformational mode of the dented tubes.

DCF failure mode

This mode of failure was observed for the severest case of damage to the specimens. As can be seen in Fig. 12, no crack occurred on the tension side of the specimen. It appeared that the deformational energy was fully absorbed in the dented area. Hence, fatigue cracks occurred in the trough zone of the dent (see Figs. 14 and 15), and the specimen failed owing to the severe deformation on the compression side of the damaged section. This phenomenon can be directly attributed to a high rate of stress concentration in the concave zone of the dented area, exceeding the stress concentration at the T-joint near the weld-toe of the brace. Figs. 14 and 15 show the dent-imposed crack and the failure modes of CLC.6 specimen.

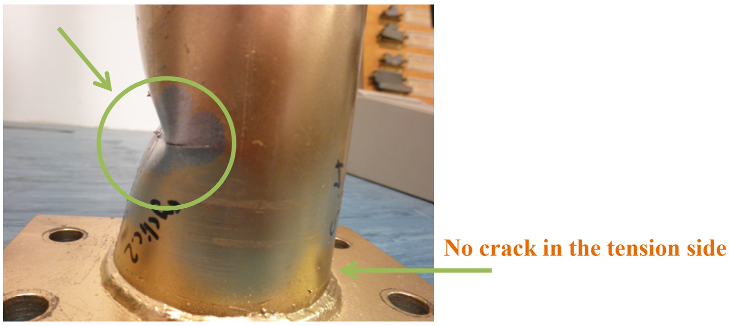
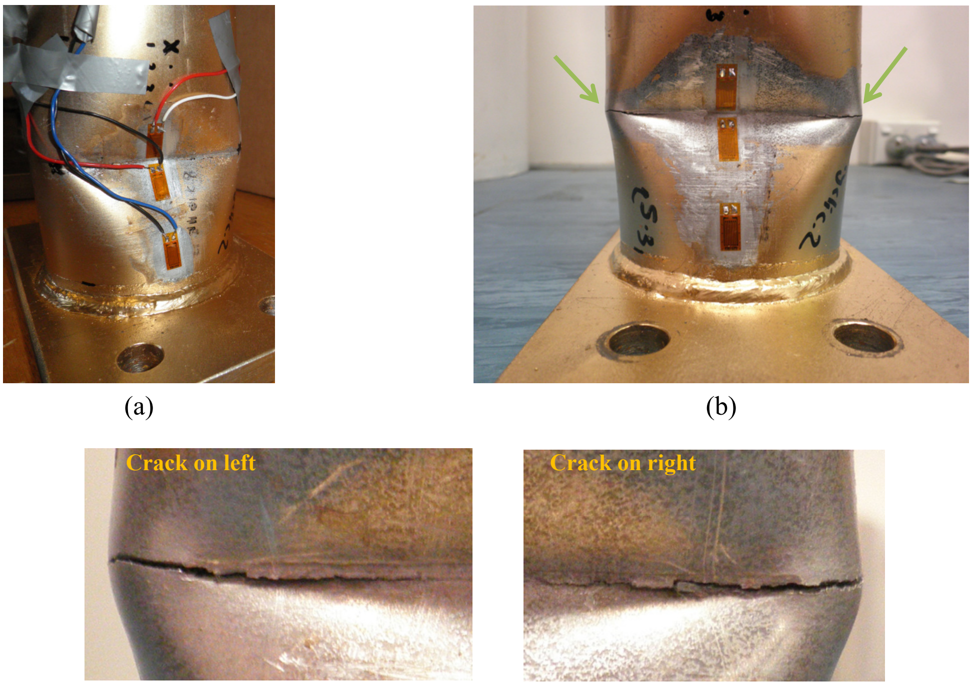


Fig. 14 Dent-imposed crack after failure for CLC.6



(a) (b)

(c)

Fig. 15 (a) CLC.6 before testing; (b), (c) CLC.6 after failure

4. Fatigue life

4.1 Fatigue life of the current specimens

Fig. 16 relates the fatigue life of the specimens to the severity of the damaged area. As can be seen in Table 3 fatigue life was strongly related to the intensity of the collision, subsequently the size of existing dent so that the more the depth of the dent the less the fatigue life. All tests were conducted within the same load range in order to evaluate the effect of the different dents. As tabulated in Table 3, CLC.6 specimen with d/t = 8 lost 85.2% of its fatigue life compared with the intact specimen. In fact, this reduction is substantial indicating the significance of the damage. Likewise, a reduction of 65.5% was observed for CLC.5 in which the dent′s depth was nearly five times more than the thickness of the shell. In a similar way, the effect is still remarkable for the specimens with moderate value of the dent (e.g., CLC.4 specimen); however, this effect is not as critical as more severe dents. Bearing in mind that for the CLC.4 specimen the capacity was decreased by around 30%; whereas, the effect of the dent was quite negligible for the slightest dent which was equal to the thickness of the tube (see Table 3).

4.2 Crack initiation and strain behaviour

Fig. 17 shows the distribution of the strain gauges on different points of the specimens. Figs. 18-20 present strain values versus the number of cycles in three different specimens of CLC.2, CLC.5 and CLC.6. As can be seen, S.1 and S.2 were put on the dented area and S.4 was stuck near

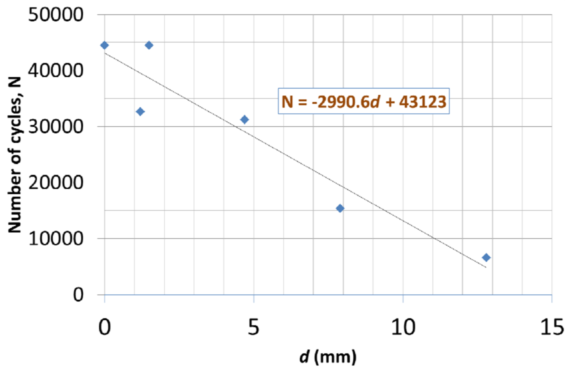


Fig. 16 Fatigue life versus the severity of the damaged area

Table 3 Fatigue life and failure modes

Test	d (mm)	d/t	Number of cycles	Difference in fatigue life (%)	Failure mode
CLC.1	0	0	44482	0	BTS
CLC.2	1.2	0.75	32630	26.65	BTS
CLC.3	1.5	0.94	44455	0.06	BTS
CLC.4	4.7	2.94	31210	29.84	DWF
CLC.5	7.9	4.94	15334	65.53	DWF
CLC.6	12.8	8	6592	85.2	DCF

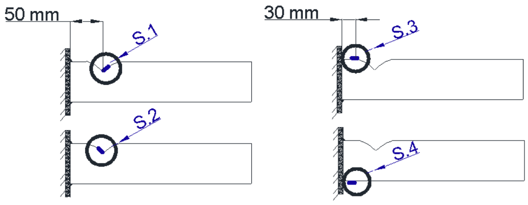


Fig. 17 Position of strain gauges

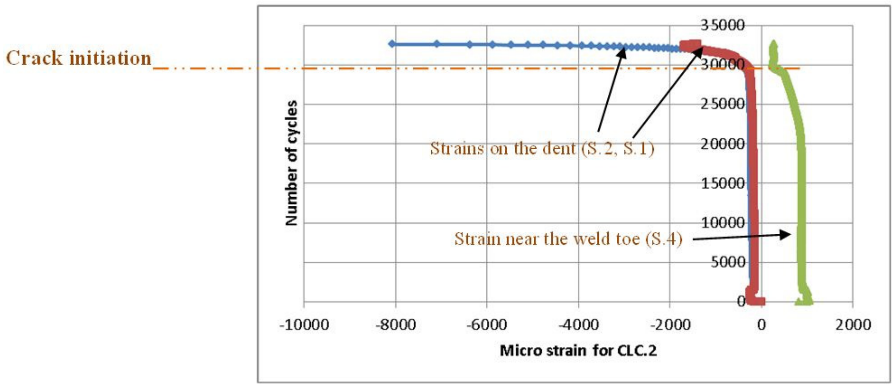


Fig. 18 Strain versus number of cycles in CLC.2

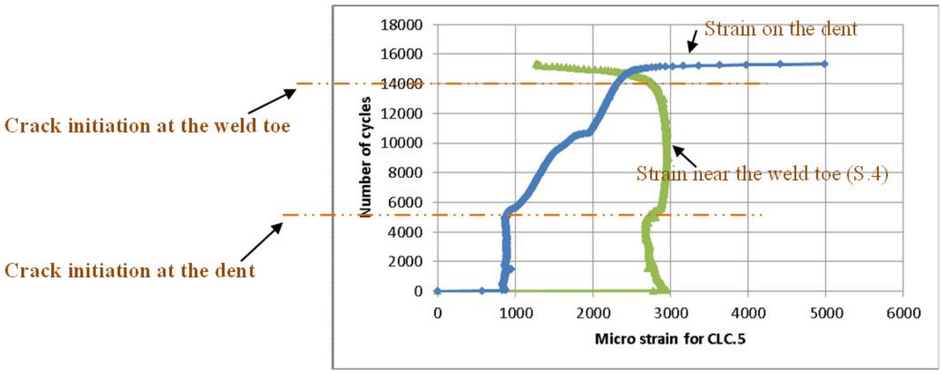


Fig. 19 Strain versus number of cycles in CLC.5

the weld toe of the tension side which was the zone of maximum tensile stress. As mentioned earlier, the failure mode for CLC.2 was *BTS mode* of failure which was recorded on the strain data. Fig. 18 shows that the strain values near the welding became non-linear when the crack was initiated near the welding toe. After the initiation of the crack, the strain values in the dented area increased dramatically indicating that the deformations were largely absorbed in the dented region. This was followed by the development of the crack and eventually the failure of the specimen. Fig. 19 shows the strain values for specimen CLC.5 in which the *DWF mode* of failure occurred. As marked on Fig. 19, the first increase in the strain curves at around 5000 cycles was corresponding

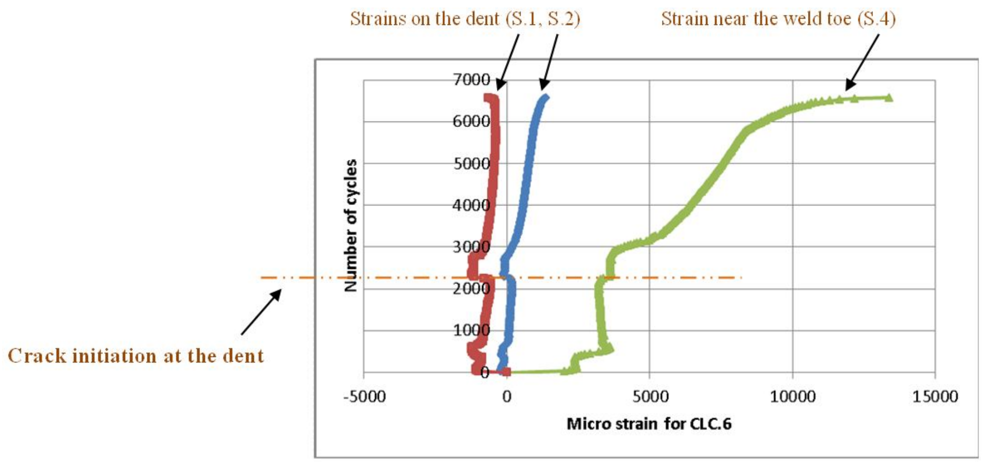


Fig. 20 Strain versus number of cycles in CLC.6

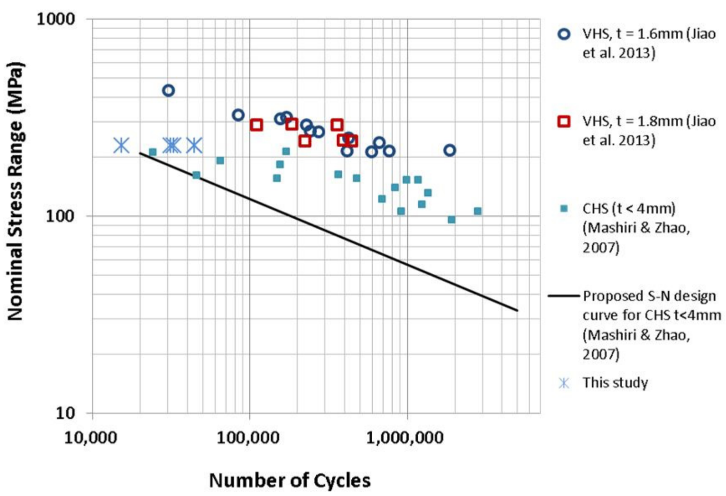


Fig. 21 Comparison of the data of this study with VHS and CHS plate, T-joint data

to the crack initiation at the dented area after which the overall trend of the strain curves was almost stable until the second crack occurred near the weld toe at around 14000 cycles. This crack was accompanied by severe nonlinearity of the curves leading to the failure of the specimen. For specimen CLC.6, failure was due to the crack initiation at the dented area, i.e., *DCF mode* of failure. Crack occurred due to the severe geometric irregularity of the dented area well before the final failure of the specimen. As can be seen in Fig. 20, after the initiation of the crack, a little fluctuation is seen in the curves after which the curves reached a stable condition leading to the final failure which was accompanied by a nonlinear behaviour at the dented area.

4.3 Comparisons with other works

In order to compare the results of the current study, the method of nominal stress range versus the number of cycles as a plot on a log scale is adopted. Since CHS-plate T-joints fatigue results

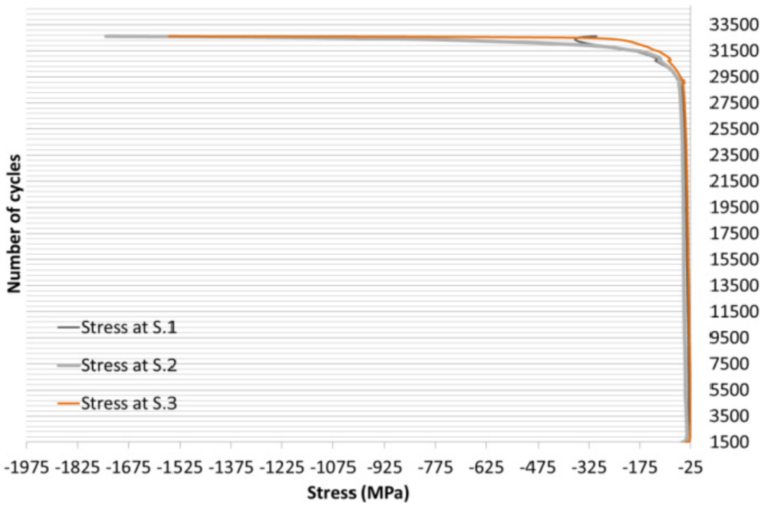


Fig. 22 Measured stress versus the number of cycles in CLC.2

have not been reported for the in-plane bending in existing standards as a design guide, the data provided by Mashiri and Zhao (2007) is taken into account to evaluate the current experimental results. As can be seen in Fig. 21, for the intact specimen the present test data is well consistent with the chart so that the validity of the testing program and the results can be satisfactorily confirmed. On the other hand, the impact of the dent imperfection can be clearly observed within the chart, accordingly this comparison provides a significant insight into the influence of the damage on the fatigue life considering the results of the mentioned study on cold formed CHS-plate and T-joints under in-plane cyclic bending load.

Moreover, a typical measured stress range for the compression zone at/near the dent imperfection was plotted in Fig. 22 for specimen CLC.2. As is shown, the stress was approximately uniform only with a slight slope up to around 29000 cycles after which the stress started to increase in a non-linear manner which can be considered as the final phase of the fatigue life of this specimen.

5. Conclusions

An experimental study on dented tube specimens with D/t ratio of 47.6 was conducted in this research. The specimens were subjected to cyclic bending moment. The fatigue life and the failure modes of such structures were discussed in this paper. The key findings of this investigation are outlined as follows:

- Three different failure modes were obtained from this experimental program.
- *BTS mode*: This mode of failure occurred beside and along the welding at the tube specimens for the models with relatively small rate of d as well as the intact specimen. This mode is called brace-tension-side mode of failure (*BTS mode*).
- *DWF mode*: This mode occurred both in dented zone and near the welding for the specimens with medium rate of the dent severity.
- The movement of the dented area under cyclic loading was quite interesting and fairly

similar to the beating of a heart with a regular rhythm so that pre-failure phase was referred to as *Heartbeat Mode*.

- *DCF mode*: For this mode of failure crack happened in the trough zone of the dent. While, there was no crack in the tension side of the specimens. This mode of failure was detected for the severe case of the damaged specimens.
- Although the dented region was in the compression side, the fatigue crack occurred in the dent itself due to the local shape irregularities of the damaged section. This was strongly attributed to the intensity of the collision and subsequently, existing dent as the more the dent′s depth the less the fatigue life.
- The specimen with d/t = 8 lost 85.2% of its fatigue life; whereas, for the slightest dent equal to the thickness of the tube, the decreasing effect was quite negligible.
- The present test data is highly consistent with the results of previous works. What's more, the reducing impact of the dent imperfection can be clearly observed within the chart.

Future works

This paper is a first step on the effect of damaged areas on the fatigue behavior of CHS members. The existing standards and design codes have mostly focused on ordinary fabrication related imperfections. Notwithstanding this, further researches into large and local imperfections are still needed to extend the current knowledge and accordingly to use the data for designing dented members in practice. In fact, the tolerance values pointed out in the existing standards may not fully cover the needs in practice to estimate the final capacity of the dented elements for maintaining the structural members during their service life. As such, further tests are required on vast variety of large imperfections such as dents and gouges to develop thorough design guidelines in this regard.

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Fig. 1 from: http://services.eng.uts.edu.au/~alis/public_html/Research/grouted_tubular_members.htm

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