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RESIDUAL STRESS EFFECT ON LINK ELEMENT OF ECCENTRICALLY BRACED FRAME

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Abstract

The effects of residual stress on the performance of link elements as lateral force shield, particularly for earthquake load as in the Eccentrically Braced Frame (EBF), is the main focus of this research. Experimental tests were conducted in two stages: first, the residual stress measurement of the link element with Neutron Diffraction Method methodology using the equipment of DN1-M PSTBM BATAN; second, two links were tested, a standard link that corresponds with the AISC 341-10 and a modified link. Behaviours of both links were studied based on the residual stress distribution in the first stage. The magnitude of tensile stresses on and around the “k area” caused the initiation of crack on the standard link so that it decreases the performance of the link element. Modifications of the link by replacing the stiffener of vertical web with the horizontal stiffener can avoid the initiation of crack that may occur on the web plate around the “k area” so that the performance of the link elements can be improved.

Keywords: Residual stress; Neutron Diffraction Method; k-area; horizontal web stiffeners; EBF.

1. Introduction

The k area is the joint area between the plates of stiffener-web and flanges of the link elements. According to the AISC341-10, this area is used as an access for welding and is stipulated to have a width of 38 mm. The research by Kurdi et al., 2014, shows that this area has high magnitude and distribution of tensile stress and is vulnerable to crack failure.

Residual stress due to heat may cause deformation during the welding process that is quite high on the area around the welding surface in the direction of the plate's thickness. Combined with the cyclic loading, as in the case of the EBF link elements, residual stress will be likely to initiate a crack on this area.

A number of tests in previous research (Arce, 2004; Okazaki et al., 2005; Yurisman et al., 2010; Moestopo and Panjaitan, 2012) have documented several occurences of crack on the web or flange of the link elements. The crack on the "k area" that is a failure on the web close to the stiffener, or is commonly identified as the Heat Affected Zone (HAZ) area, is not only experienced by the intermediate and long (flexure) links, but also occurs on the short (shear) link. This occurence is shown Figure 1. However, the cause of link failure has not been much investigated until now.

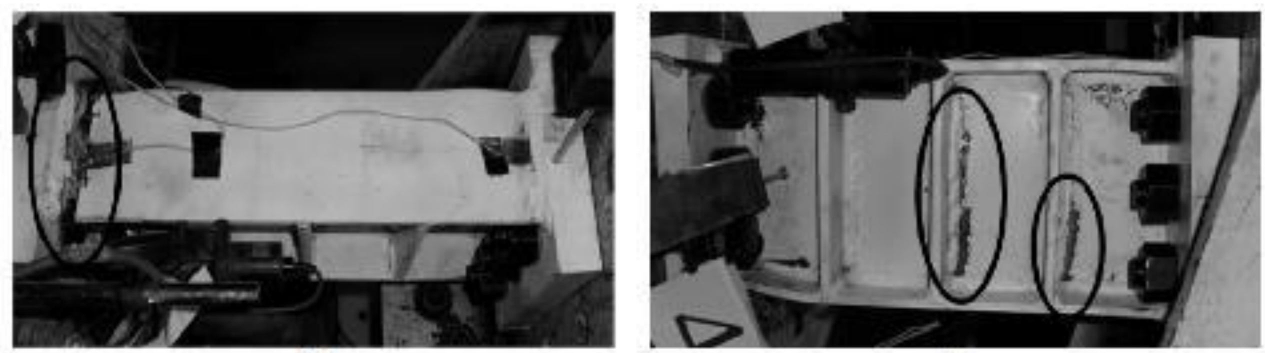


Fig. 1 - The failure incident of "k area" of the link (Moestopo and Panjaitan, 2012)

We first hyphotesized that amongst other causes, the incident is occurred due to residual stress during the welding process that induces the hydrostatic stress effect on the HAZ area, which in turn, causes the fracture failure. The crack is caused by a decrease in plastic deformation on the link element, which causes a failure (crack) that is sudden (brittle) that occurred both on the k area and the joint of plate's ends. This effect has caused an inelastic rotation capacity of the link, so that the AISC 341-10 stipulation cannot be achieved.

In terms of its application in civil engineering, the effect of residual stress until now has not been explicitly calculated on the joint between one plate and another, particularly for steels of high quality. Therefore, a good prediction of residual stress effect due to welding is required for the use of a joint of one plate to another. Furthermore, this research is performed to understand more details of the magnitude and distribution of residual stress on and around the k area in the light of performance improvements of EBF link elements, which to date has not been investigated by other researchers.

2. Experimental Tests

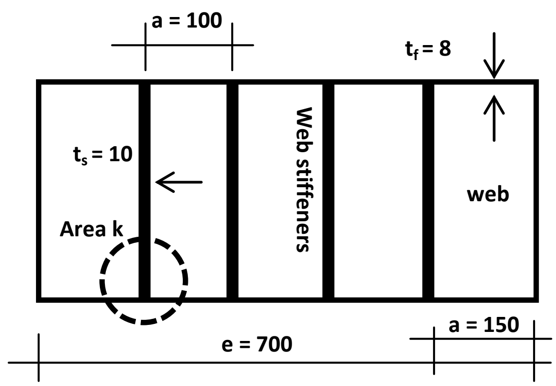
The experimental tests in this study was conducted in two stages. The objective of the first test is to obtain the residual stress magnitude and distribution, whereas the second test is performed to study the behaviour and performance of the EBFS link element. Details of both tests are further described as follow :

2.1 Residual stress measurement

This study used a non-destructive method by the neutron diffraction techniques. Due to the absence of electricity charges, the neutron can interact with the nuclear of the atoms of the constituent material and is able to pass through the material until several centimenters deep. This unique characteristic allows the measurement of the direction of residual stress to be performed as desired. Details of the measurement is further described in Budiono et al. (2016).

The residual stress measurement was performed using the Difractometer Neutron DN1-M equipment of PTBIN BATAN which is installed on the beam tube number 6 (S-6) in RSG GAS BATAN in Serpong. Two samples were used with varying extent of k area, which is 100 mm^2 or RSK10x10 mm, and 200 mm^2 or RSK20x10 mm as shown on Figure 2. Details of the dimension from each of the samples are shown in Table 1.

Details of the link element



Crosscut section of A- A

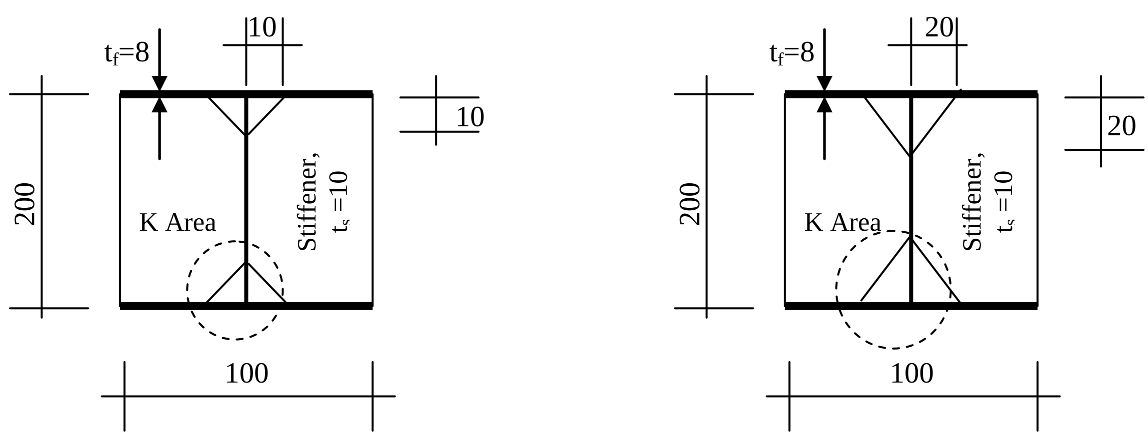


Fig. 2 - Variation of k area extent from the measured samples: a. RSK10x10 b. RSK20x10

Table 1 - Dimension of RSK100 and RSK200 samples

Sample	Profile	Distance of Stiffener (mm)	Thickness of Stiffener (mm)	Thickness of Web (mm)	Thickness of Flange (mm)	Extent of K Area (mm2)	Length of Link (mm)	Number of Stiffener (both sides)
RSK100	WF200.100	100	10	5,5	8	100	400	1
RSK200	WF200.100	100	10	5,5	8	200	400	1

Furthermore, direction and the points of measurement are shown in Figure 3.

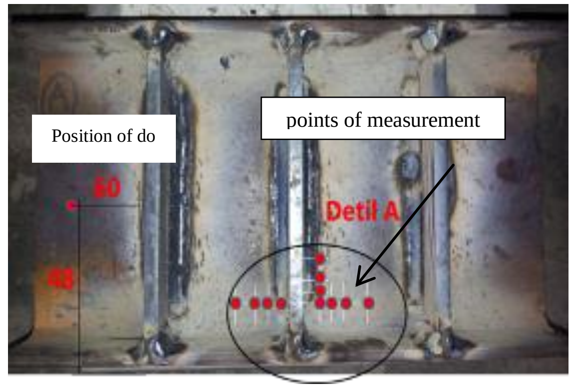
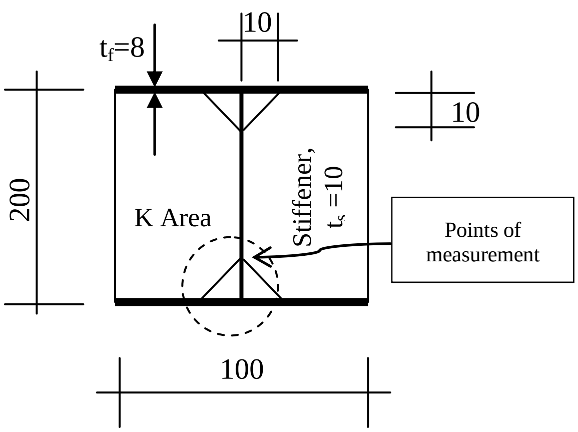


Fig. 3 - Direction and points of measurement on the residual stress measurement

The measurement was conducted with a diffraction angle of 1,030 for the plane of 211 from the Miller's index with 1.836863 wavelength. The slit incident beam has 3x3 mm dimension and the detector beam has 7 mm radial colimator. Each of the measurement points was measured within 60 minutes in the normal direction and 90 minutes in the transversal and longitudinal directions. Details of distance of each of the measurement points is shown in Figure 4. The measurement in this study was only conducted for the point 5, 6, 7, 8 and 9 as shown in Figure 4.



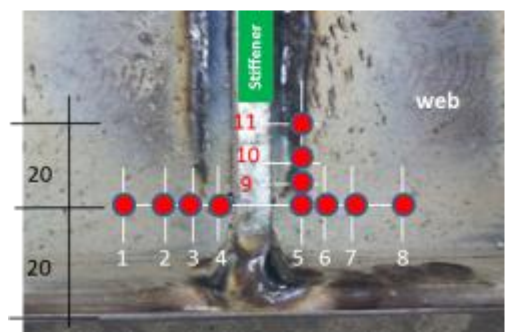


Fig. 4 - Detail of residual stress points of measurement

The measured parameters are described in Table 2.

Table 2 - Values of parameters in the experiment

λ(Å)	**2θ (°)**	**θ(°)**	**A(Å)**	**d**	**Miller's index (hkl)**	**Period on one point**	**Slit Incident Beam**	**Slit Detector**
1,836863	103	51,5	2,87	1,15	211	90 minutes	3x3 mm	Radial colimator 7

In this study, the fillet welding as is stipulated on the AISC 341-10 was constructed between the stiffener plate, which is 136x34 mm and 10 mm thick, with the web and flange plates. The welding procedure is arranged in accordance to the AWSD1.1 2008. Prior to the welding process, the surfaces of stiffener plate and profile were cleaned from dust and debris. The profile is supported by other plates on both ends in order to avoid distortion during the welding process. The welding begins with the welding of points to secure the position of stiffener plate on the center of the web/flange plates.

The welding process is performed by hand using the method of Shield Metal Arch Welding (SMAW) with the stages of welding that begins with the welding of stiffener plate with the web plate, and then the stiffener plate with the flange plate in clockwise-direction. The same method is performed for other parts as well.

The neutron diffraction method can be used directly to measure the strain by measuring the distance of crystal lattices. The stress value may be calculated in three directions using the Equation (1).

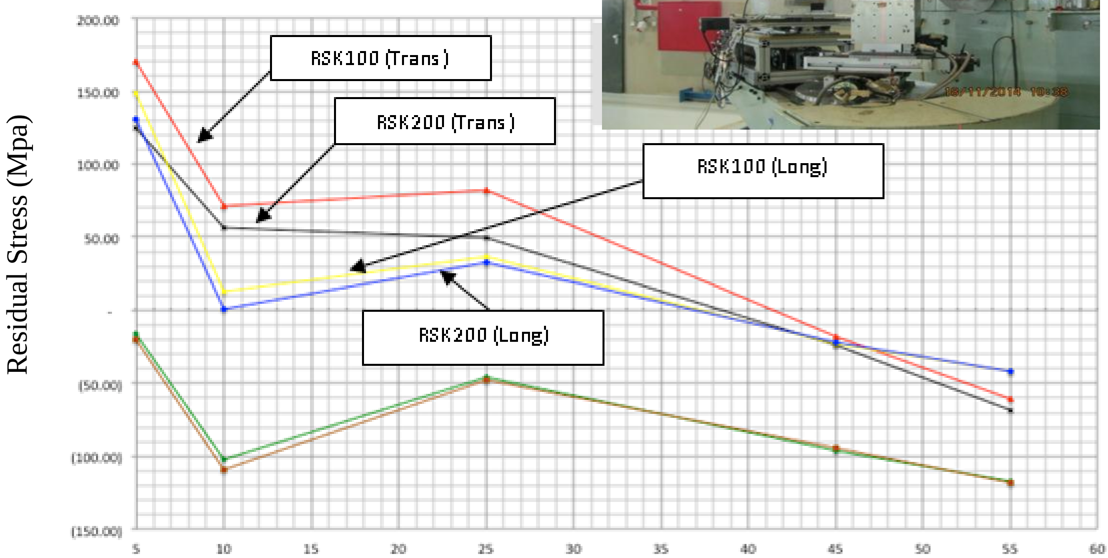
$$\sigma_i = \frac{E_{211}}{(1+v_{211})}\left\{\frac{\varepsilon_i + v_{211}}{(1-2v_{211})(\varepsilon_Z+\varepsilon_y+\varepsilon_x)}\right\} \qquad \text{where } (i = X, Y, Z) \qquad (1)$$

By using the Equation 1, with E211 value of 2,106 Mpa and v211 of 0.3, hence the results of residual stresses are listed in Table 3 and described in Figure 5.

Table 3 - The value of residual stress in normal, transversal and longitudinal directions

The measured points	Points of measurement Position (mm)	Stress in Normal Direction (Mpa)		Stress in Transversal Direction (Mpa)		Stress in Longitudinal Direction (Mpa)	
		K10x10	K20x10	K10x10	K20x10	K10x10	K20x10
Y5	5	-15,64	-18,77	170,28	149,63	148,19	124,14
Y6	10	-116,83	-137,86	23,59	16,98	-94,10	-81,65
Y7	12	-125,26	-137,78	-19,97	-15,38	-167,26	-147,79
Y8	22	-61,82	-60,58	-24,71	-24,22	-115,26	-114,46
Y9	42	-5,26	-5,21	-51,93	-51,65	-70,93	-69,43

a. Measurements in transversal direction



Measurement Position in Y Direction (mm)

b. Measurements in longitudinal direction

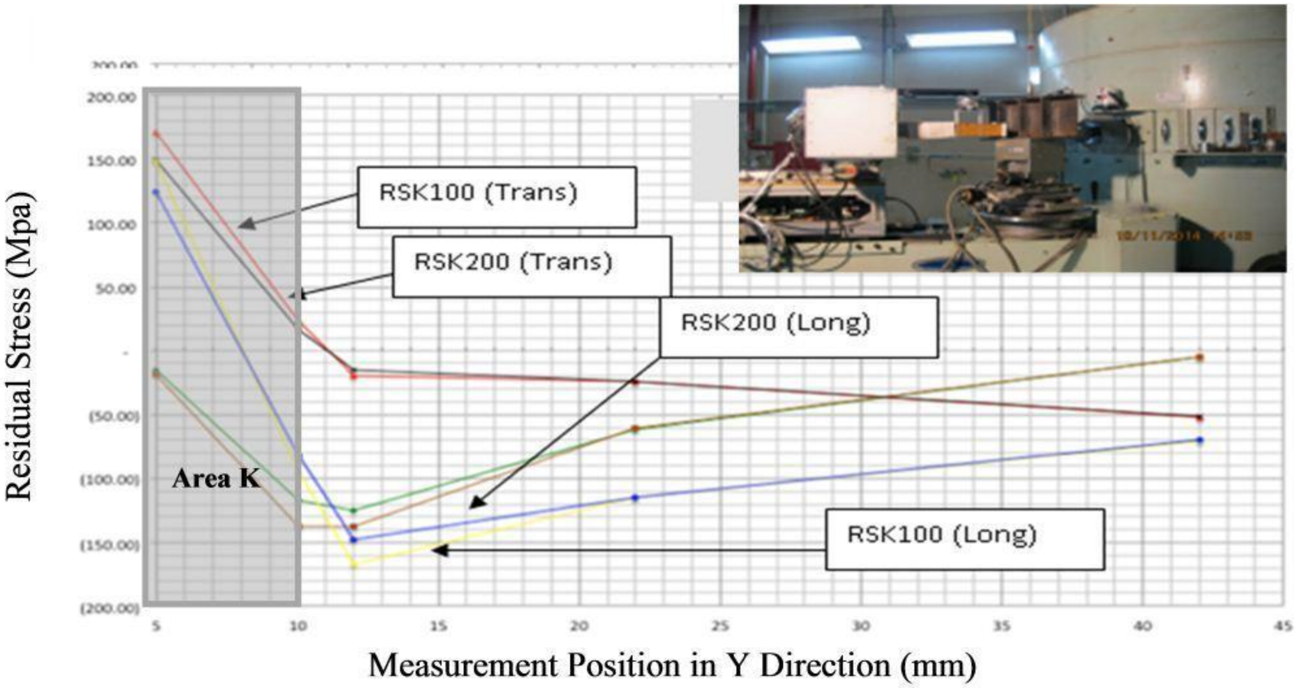


Fig. 5 - Results of measurements of both samples

The graphs in Figure 5 show that the pattern of distribution of residual stress on the welding area is well distributed both in transversal or longitudinal directions for both samples, RSK100 and RSK200. Furthermore, the area around the weld toe has a positive value (tensile stress) that continuously decreases on the HAZ area and turns to negative with increasing distance to the weld toe. This is because the heat that was received by parts of the link elements aroung the welding points (weld pool) was higher compared to the heat on the HAZ area and the web ends plate during the welding process.

Figure 5 also shows a quite significant difference on the weld toe area between the k area of the K10x10 and RSK200 samples in the transversal and longitudinal directions. The high value of residual stress on the areas of weld toe and around the k area of the link may initiate cracks on the k area during the application of external load.

Furthermore, the figure shows that welding avoidance on the k area (RSK200 sample) has resulted in less residual stress magnitude and distribution around the weld toe and HAZ area. Considering the high tensile stress that occurred on and around the k area, hence this treatment is considered to be quite significant during the test of the link samples that will be subjected to external loads. The observed link behaviour, as shown in Figure 1, shows that the crack initiates on the k area. By avoiding the welding process, the crack initiation may be slowed down on the k area of the link element.

The results of the tensile stress tests show that the yield stress value (fy) on the center of the web plate is 315 Mpa with the ultimate stress of 490 Mpa. These values are slightly different with the tests conducted on the k area that reaches 318 Mpa and 497 Mpa for the yield stress (fy) and ultimate stress (fu), respectively, as shown in Figure 8a.

Furthermore, the experiment shows that the value of residual stress obtained on the weld toe area is within the interval of 75 to 85 % of the yield stress of material and tend to decrease on the HAZ area that ranges between 50 to 60% of the yield stress both in transversal or longitudinal directions. Furthermore, the width of tensile area reaches 6 times wider compared to the web plate in terms of residual stress in transversal direction and 4 times wider in the longitudinal direction.

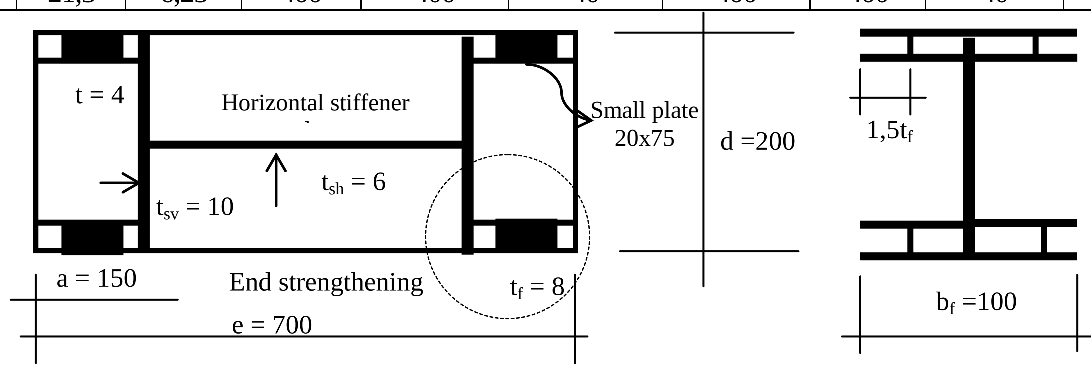
2.2 The cyclic test of the link elements

The second stage test used two links with 700 mm length. This length is used considering the greatest value of shear and moment forces, as it is located on the transition area between the shear and intermediate links. There are two links that were tested. One is the standard link that is designed according to AISC 341-10, as detailed on Figure 2, and another one is the modified link. Both links used the WF200.100 profile.

The modified link was using the horizontal stiffener plate in order to avoid the high residual stress on the k area, as is shown in the results of the residual stress measurement. In addition to the use of horizontal web stiffener, the end part was also strengthened by adding the stiffener plate that was positioned in parralel with the flange plate. The function of the end plate is to avoid buckling and increase the capacity of the sectional area. Details of dimensions of the modified link is shown in Table 4 and Figure 6.

Table 4 Dimension of the link element samples (all units in mm, except if mentioned earlier)

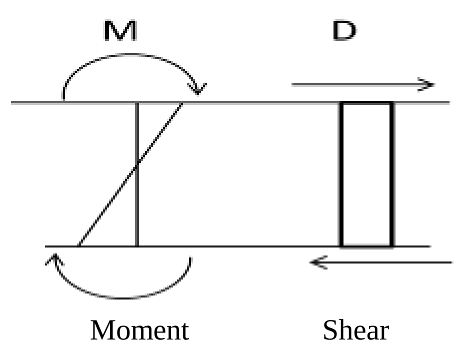
Profile	Width (b)	Height (d)	Link length (e)	Web thickness (t_w)	Stiffeners thickness (t_s)	Flange thickness (t_f)	Vp (KN)	Mp (KNm)	$(e.V_p)/M_p$
WF200	100	200	700	5,5	10	8	230,7	74,7	2,16
Stiffeners thickness (a)	Vn (T)	b/2tf	Upper plate			Lower plate			Rotation (rad)
			width	length	thickness	width	length	thickness	
100	21,3	6,25	400	400	40	400	400	40	0,0464



a. Overview of the modified link
b. Crosscut section A-A

Fig. 6 - Details of samples of the modified link element (in mm)

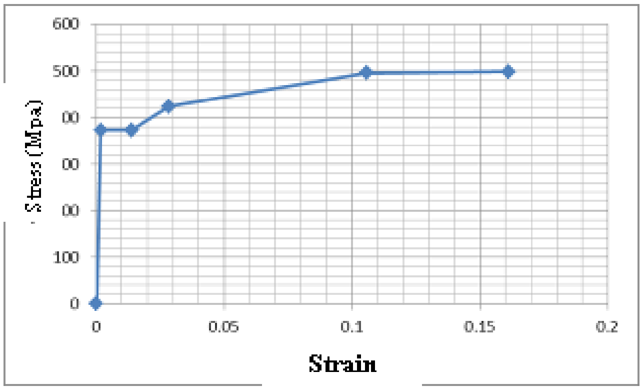
Furthermore, the set up for the tests and distribution of forces on the link are shown in Figure 7 as follow :



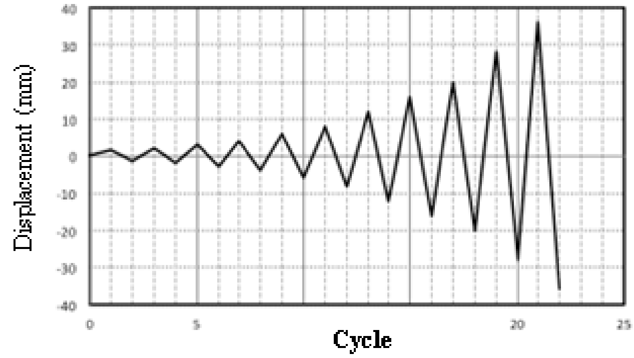
a. Set up for the test
b. Distribution of forces

Fig. 7 - Set up for the tests and distribution of forces

Furthermore, the curve of residual stress and strain resulted from the tensile stress and load pattern are shown in Figure 8.



a. Curve of stress-strain



b. Loading pattern

Fig. 8 - Curve of stress-strain and loading pattern

Positioning of each of the LVDT is shown in Figure 9.

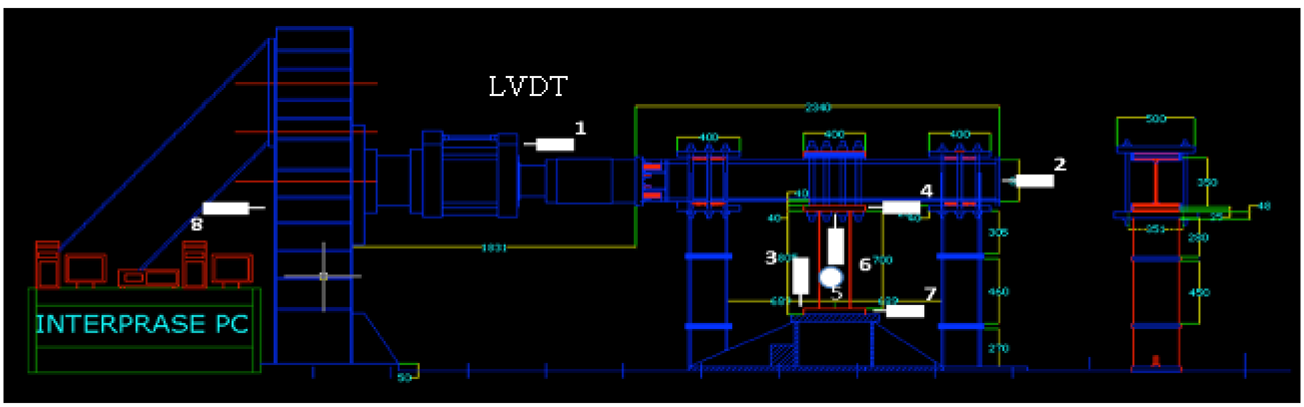


Fig. 9 - Position of LVDT placement

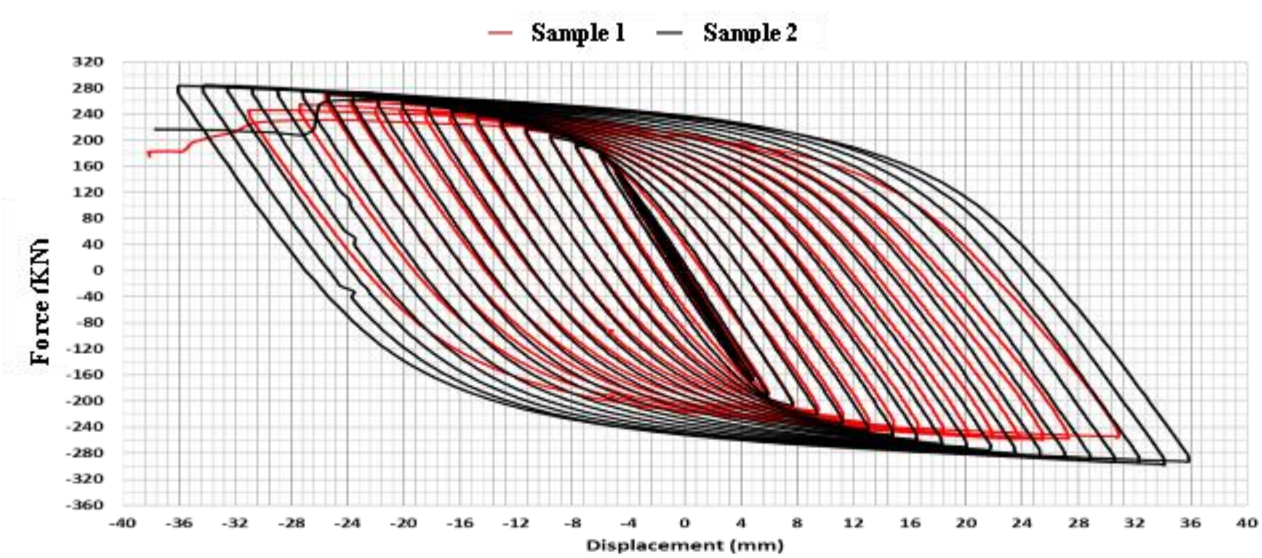


Figure 10 - A comparison between the hysteristic curve of the standard and modified links

The test results show a comparison of the hysteristic curve of standard link (sample 1) with the modified link (sample 2) as in Figure 10 below.

The figure shows that the standard link experienced failure on the flange end of the link elements when the placement was reaching 28 mm, however the modified link was still in normal condition without experiencing any failure; its placement was even reaching 36 mm. Link modification by avoiding the formation of k area on the link is therefore, may slow down the initiation of crack and increase the ductility value. Several failures of the standard link and the behaviours of the intermediate link are shown in Figure 11 below.

The collapse patterns of the standard and modified links

a. Standard Link b. Modified Link

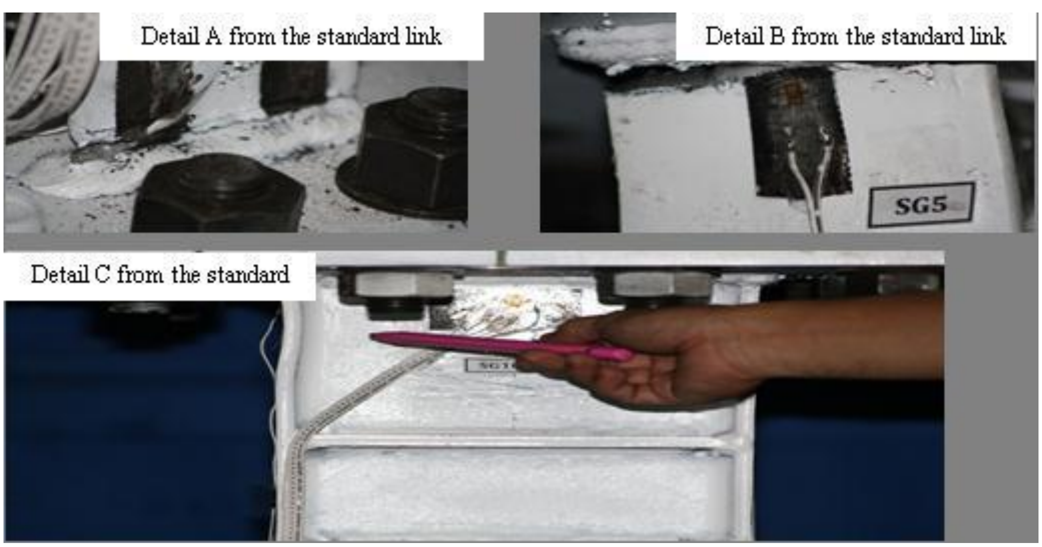


Fig. 11 - A number of failures on the standard link

3. Conclusion

Based on the above results, the conclusions are as follow:

a. The residual stress distribution pattern on the welding area that was performed by experiment has the same results both in the transversal or longitudinal direction. Furthermore, the residual stress on the area around the weld toe has positive value (tensile stress) that continuously decreases on the HAZ area and turns to negative with increasing distance to the weld toe point. This is because the heat that was received on the area of weld toe is far greater than on the external area.

b. The value of tensile stress that was obtained using the neutron diffraction method measurement on the weld toe area is within the interval of 75 to 85 % of the yield stress of the material and tend to decrease on the HAZ area that ranges between 50 to 60 % of the yield stresses in the transversal and longitudinal directions.

c. The modified link element behaviour by the addition of horizontal stiffener, that was performed in order to avoid the k area which may cause high tensile stress, was showing an increase in the ductility of the link element. Furthermore, strengthening the flange end plate was also proven to slow down the buckling process. Figure 10 shows that the modified link element has improved performance compared to the standard link. Avoiding the k area that has high tensile stress value may increase the link element performance because the ductility value can be increased.

d. As a footnote from Figure 10, that if the link design calculates the residual stress value then the link capacity (Vu) has to be adjusted by multiplying it with a coefficient that is smaller than 1. This constant value is a coefficient that takes into consideration the influence of residual stress. The determination of this coefficient value is a topic that requires further research.

4. Acknowledgements

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