# MEASUREMENT OF WELDING INDUCED DISTORTIONS IN FABRICATION OF A PROTOTYPE DRAGLINE JOINT: A CASE STUDY

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**ABSTRACT**

Discontinuous welding of hollow tubular members is an important joining process in structural applications like dragline booms, cranes, pipelines, ships and bridges. The non-uniform temperature fields generated by the plume of heat energy emanating from the weld torch invariably create undesired distortions in the parent metal that negatively influence the fabrication accuracy and physical appearance. The load bearing ability and effective strength of members is further compromised by the unmitigated residual stresses that are usually left untreated owing to huge costs, long time-frames and the general infeasibility of post weld heat treatment processes. This paper presents a case study reporting the measurements of welding induced distortions in a four-member, circular hollow section tubular joint fabricated as a prototype cluster of a much larger dragline boom. Measurements were taken in a workshop setting with a coordinate measuring laser machine and were collated and analysed for predictions about the overall effect and implications of distortions. It was concluded that in welding of members of very large structures such as dragline booms, welding induced distortions produce negligible dimensional inaccuracies which could safely be left out in the overall design process.

**Keywords:** *Cluster; Circular Hollow Section; Gas Metal Arc Welding; Distortion; Coordinate Measuring*

## 1. INTRODUCTION

Welding involves a huge amount of heat input in a very short period of time. A weldment is heated intensely during this process with a non-uniform temperature distribution that keeps altering continually as the weld torch moves along the trajectory. Welding induced distortions and residual stresses are thus created as a result of differential contractions which occur as the weld metal solidifies and cools to the ambient temperature [1-3]. Residual stresses are the stresses remaining in a material after manufacturing or processing in the absence of any external loadings, structural, thermal, or otherwise. For this reason, they are sometimes also referred to as internal stresses, or locked-in stresses. They indicate the inability of the material to return to the prior, unstressed condition after being exposed to the loading. The distortion caused by differential cooling depends on an assortment of factors and may be generated in longitudinal, transverse, or inclined directions, or any combination of these [4-6]. Both temperature and time affect the heat treatment experienced by the deposited and parent metal. Temperature distributions affect expansion and contraction and the relationship between stress and strain, and thus the microstructure properties as well as residual stresses. A large amount of work has been conducted in the last decade on measurement of weld induced distortions, the nature and origin of residual stresses, and microstructure changes, as evidenced in works of [6-16]. This research paper reports a case study of measurement of distortions in a controlled workshop setting induced by the Gas Metal Arc Welding (GMAW) of a 4-lacing dragline cluster joint, which would form one of the core nodes of a larger dragline boom. It should be noted that residual stress measurements, metallurgical evolution, or numerical simulation is not a part of this case study research.

## 2. THEORY

Four test specimens of a 4-member cluster designated 'A11' (Figure 1) were fabricated at Brisbane Engineering workshop based on the welding parameter information supplied by Bucyrus International, Inc. for one of the draglines manufactured by them [17]. The dimensions for these four specimens were chosen after careful examination of the dragline model BE 1370 in order to cover the widest validity range. The length $L_0$ of the main chord and the length $L_1$ of the protruding part of the lacings were chosen to be 2700 mm and 1000 mm respectively. The dimensions of the four specimens are reproduced in Table 1 [18].

*Table 1. Dimensions and parameters of fabricated cluster specimens.*

| Specimen | $d_0$ (mm) | $t_0$ (mm) | $d_1$ (mm) | $t_1$ (mm) | $d_2$ (mm) | $t_2$ (mm) | $\beta_1$ | $\beta_2$ | $\tau_1$ | $\tau_2$ | $2\gamma$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **S1** | 406.4 | 25.4 | 323.85 | 19.05 | 219.08 | 8.18 | 0.80 | 0.54 | 0.75 | 0.32 | 16.00 |
| **S2** | 406.4 | 25.4 | 219.08 | 8.18 | 168.28 | 7.11 | 0.54 | 0.41 | 0.32 | 0.28 | 16.00 |
| **S3** | 406.4 | 19.05 | 323.85 | 19.05 | 219.08 | 8.18 | 0.80 | 0.54 | 1.00 | 0.43 | 21.33 |
| **S4** | 406.4 | 19.05 | 219.08 | 8.18 | 168.28 | 7.11 | 0.54 | 0.41 | 0.43 | 0.37 | 21.33 |

where,

$d_0$ = Outer Diameter (OD) of the main chord,

$t_0$ = thickness of the main chord,

$d_1$ = OD of larger lacings, viz., $A_{11}H_{11}$, $A_{11}H_{12}$ and $A_{11}C_{12}$,

$t_1$ = thickness of the larger lacings,

$d_2$ = OD of smaller lacing, viz., $A_{11}C_{11}$,

$t_2$ = thickness of the smaller lacing, and

$\beta_1 = d_1 / d_0 ; \beta_2 = d_2 / d_0 ; \tau_1 = t_1 / t_0 ; \tau_2 = t_2 / t_0$ ; and $2\gamma = d_0 / t_0$.

Distortion measurements were made for all four specimens. This paper reports the measurements for specimen S2 only as a sample case.

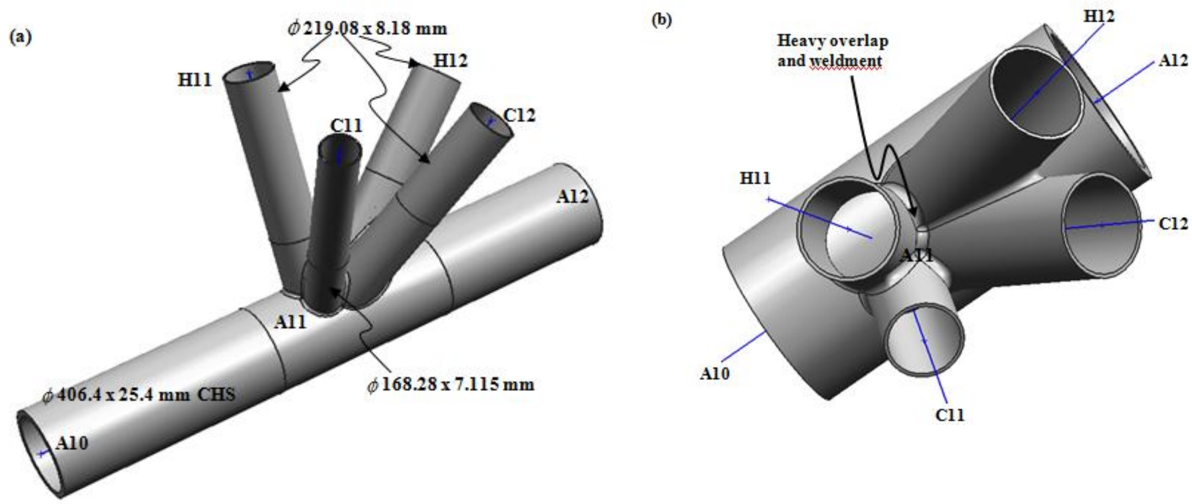



*Figure 1. (a) Part model of cluster A11, (b) magnified view of the cluster node.*

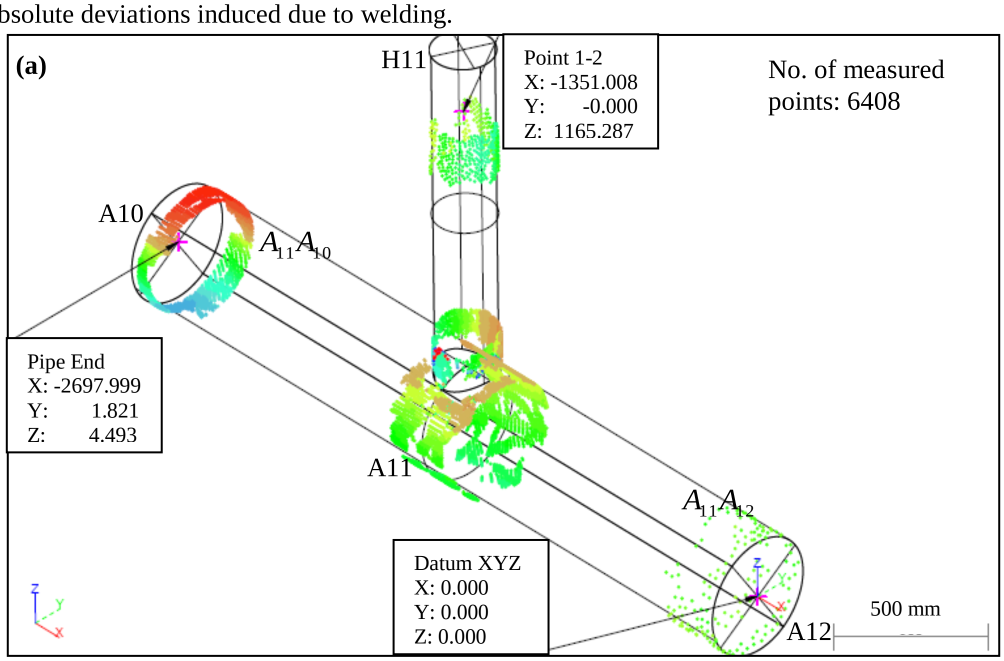
## 3. EXPERIMENTAL SET-UP AND CALIBRATION

Figure 2 shows the set-up of one of the cluster specimens (S2) during fabrication together with a portable Laser Coordinate Measuring Machine (CMM) in place at Brisbane Engineering workshop. One end of the tube with an outer diameter (OD) of 406.4 mm (main chord) was fixed as the reference point, or the origin, and coordinate measurements were taken with the laser probe for several thousand points in the node area and at the tube extremities. The distortions produced in the main chord and lacings before the start of welding and after welding each lacing were thus sequentially measured with the CMM.

*Figure 2. Fabrication of cluster A11 specimen S2.*

Measurements commenced after the first set of tack welds had been applied. It was assumed that the tack welds would make virtually no difference in the relative displacement of the main chord. Figure 3 shows the coordinates of 6408 measured points superimposed on the wire frame model of the main chord fixed horizontally and the first lacing tacked in place. The colors in Figure 3 and subsequent figures in the next section indicate the deviation of the points from the horizontal axis. The red-crosses indicate the extremities of the centerlines of the tubes, with the measured points overlaid relative to the datum position (origin). In all cases, the tube end was measured relative to the mean centre position of the tube at that end based on points measured around the circumference.

A horizontal main chord 2700 mm long, with the datum at (0, 0, 0), should have yielded the coordinates of the other extremity as (-2700, 0, 0). The measurement showed the coordinates of the extremity as (-2697.999, 1.821, 4.493). This variation may have been due to lack of straightness in the chord prior to welding, or difficulties in setting up the datum with adequate accuracy. In either case, this base deviation would be regarded as zero. The 1000 mm long vertical lacing should have shown the coordinates of its extremity, with its centerline co-eccentric with that of the main chord, as (-1350, 0, 406.4/2 + 1000), or (-1350, 0, 1203.2), instead of (-1351.008, -0.000, 1165.287) as measured by the CMM. This variation from the expected values most probably relates to inexact fitting with the tack welds, or length errors with the tubes used. Corrections were made for these zero errors subsequently (Table 2) for calculating absolute deviations induced due to welding.



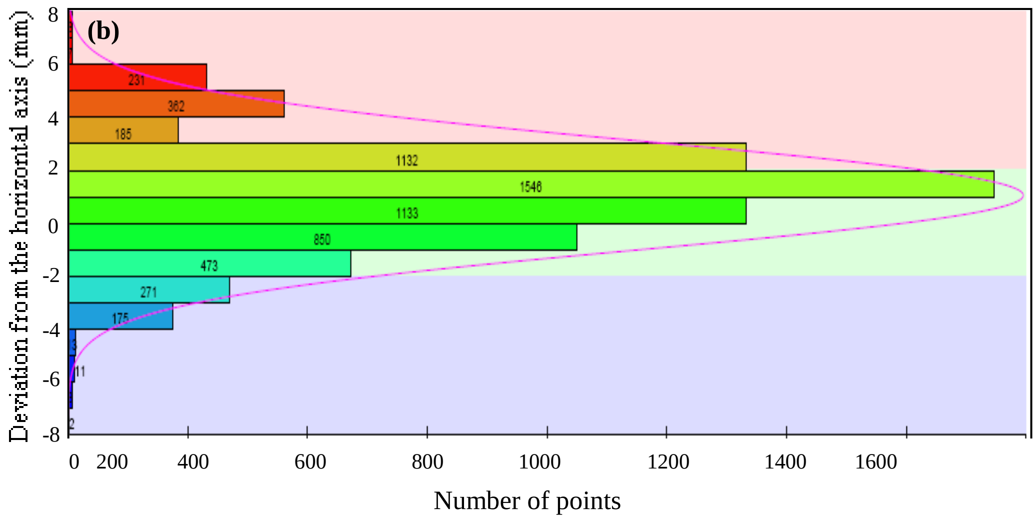



*Figure 3. (a) Main Chord and the first lacing laid out before the beginning of welding, and (b) statistics on deviation from the horizontal axis.*

## 4. MEASUREMENT OF WELDING INDUCED DISTORTIONS

Having measured and calibrated the main chord with the first lacing tacked in place, welding was performed. The second set of measurements was taken with the first lacing fully welded on to the main chord and the second lacing tacked into position. Figure 4 shows the deviations (mm) in coordinates of 7001 measured points superimposed on the wire frame model. The weldment for the first lacing was only picked up on one side and is indicated in red colour. The second lacing was tack-welded slightly out of position as indicated by the red colour on the lacing at locations adjacent the main chord and also the red crosswire at its extremity. It appears to be going in the right direction but just not passing through the node point of the cluster intersection. Nevertheless, it was relatively accurate considering the fact that establishing the centrelines of the tubes and accommodating the end cut profiles and inclination angles was a very difficult task.

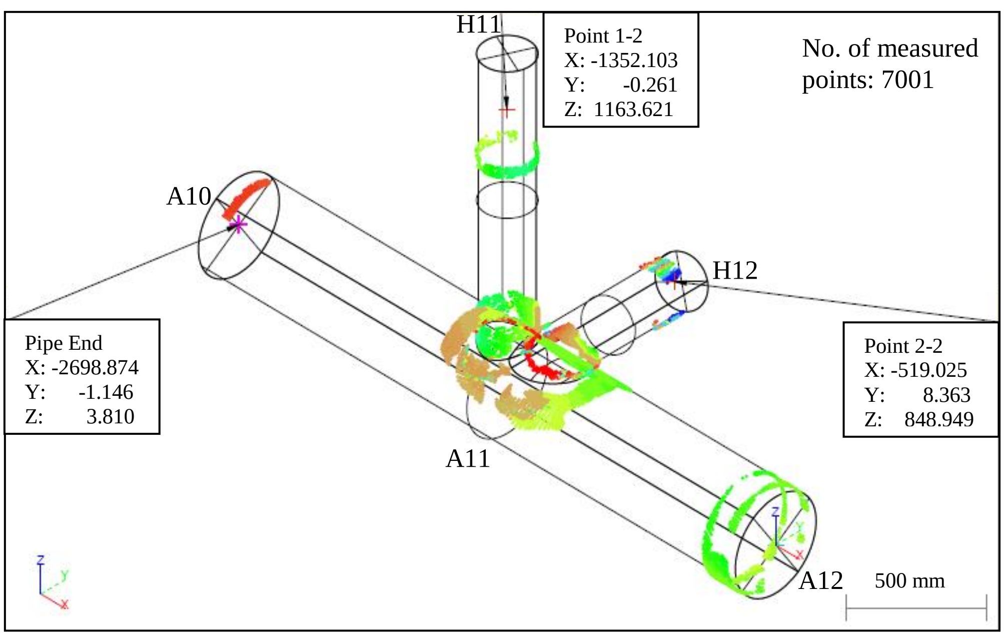



*Figure 4. Deviations measured with the first lacing fully welded on to the main chord and the second lacing tack-welded in place*

It was observed that the centre of the flame-cut end of the main chord appeared to be moving about slightly - probably due to the condition of the outside of the chord at that end along with (less significantly) the welding influences.

The third set of measurements was taken with the first two lacings fully welded on to the main chord and the third lacing tacked into position. Figure 5 shows the deviations of 3677 measured points superimposed on the wire frame model, with the same color scheme as before in the preceding figures. The second lacing was welded out of position (as it was initially tacked out of position), and it is evident from Figure 5 that the third lacing was tack-welded out of position as well.

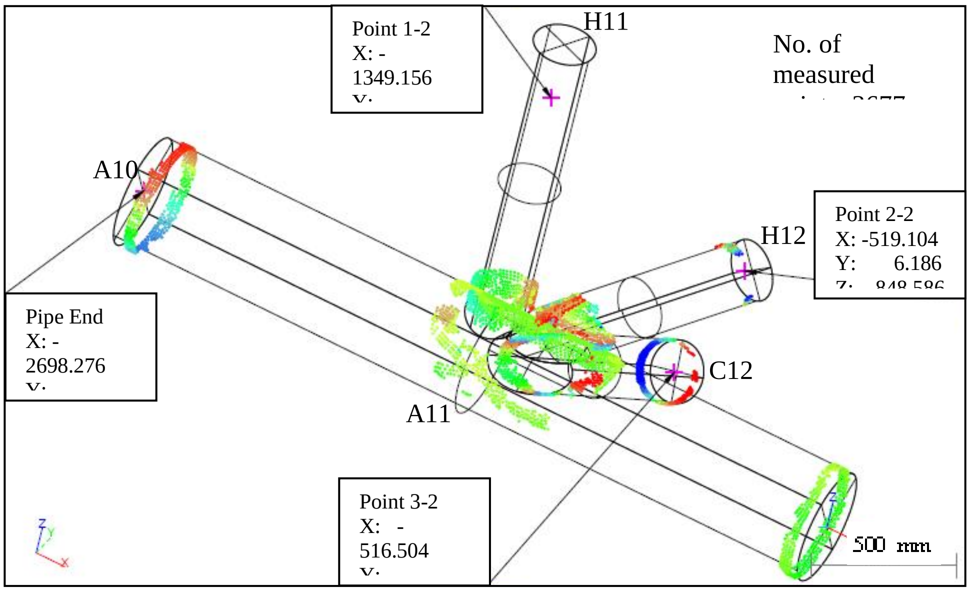



*Figure 5. Deviations measured with the first two lacings fully welded on to the main chord and the third lacing tack-welded.*

The fourth set of measurements was then taken with the first three lacings fully welded on to the main chord and the fourth and the last lacing tacked into position. Figure 6 shows the deviations in coordinates of 7774 measured points. The third lacing was welded slightly out of position, and the fourth lacing was tack-welded slightly out of position as well.

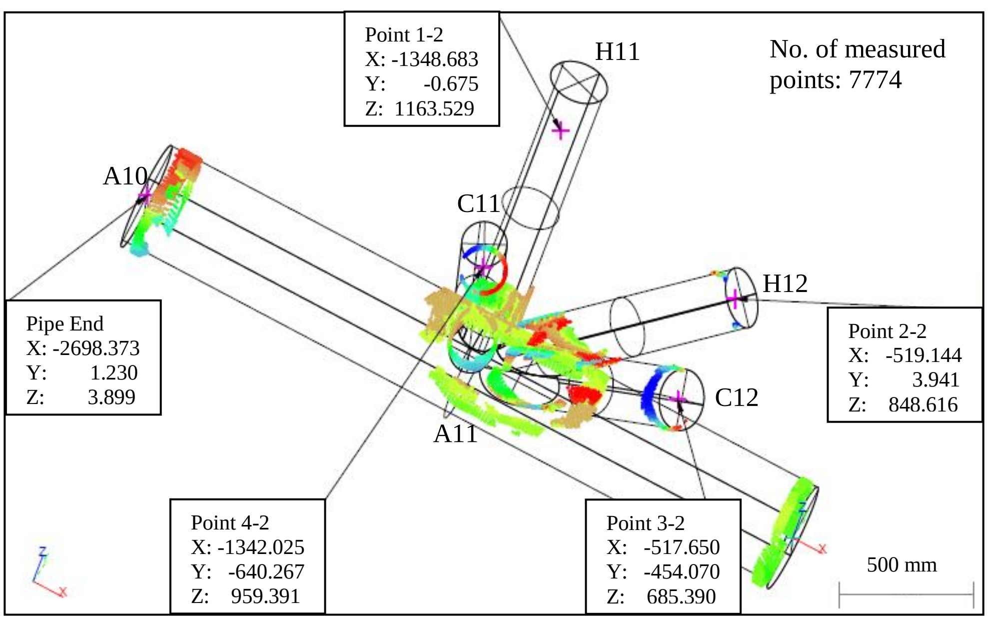



*Figure 6. Deviations measured with the first three lacings fully welded on to the main chord and the fourth lacing tack-welded.*

The fifth and the last set of measurements was taken with all the four lacings fully welded onto the main chord, and Figure 7 shows the deviations measured for 12,916 points with all the lacings fully welded in place.

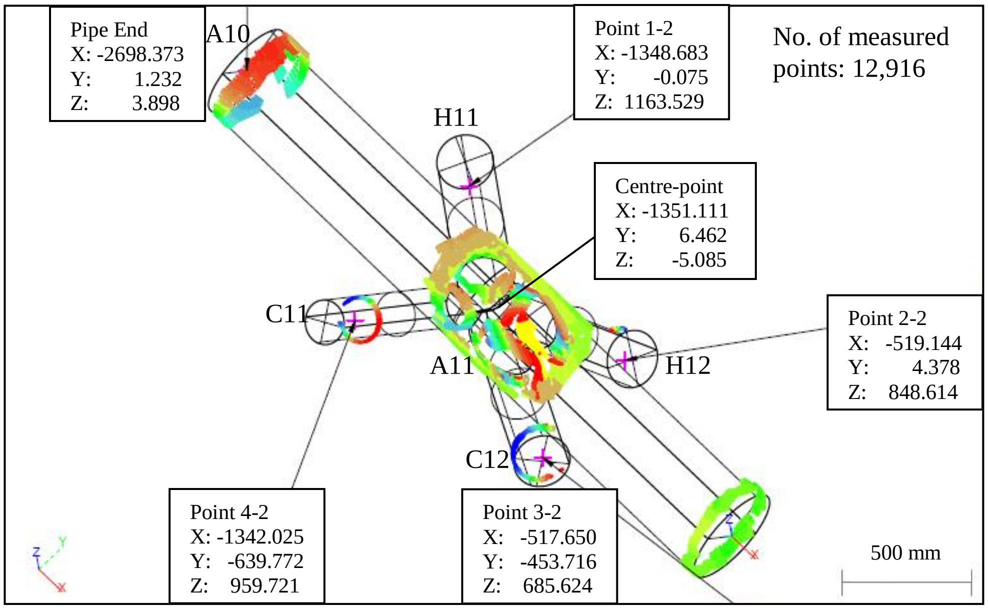



*Figure 7. Deviations measured with all four lacings fully welded.*

The last issue is the deviation of the theoretical cluster center (the theoretical point where the centerlines of all the tubes, including the main chord, intersect) relative to the X axis; averaging them all gives X = -1351.111, Y = +6.462, Z = -5.085, which should ideally have been (-1350, 0, 0).

## 5. RESULTS OF MEASUREMENTS OF WELDING INDUCED DISTORTIONS

It is evident from Figures 3 to 7 that the tubes do not move significantly in comparison to the amount of inaccuracy involved in cutting, aligning, and placing the tubes with respect to each other for welding. The results could have been more accurate if the entire end of the tubes were machined on the ends and about 25 mm back from each end on the outside to give a consistent surface to take measurements. If a suitable machining tolerance were specified, more accurate measurements could have been taken. It should also be noted that beside the welding parameters, the composition of the tube steel metal itself would influence the extent and nature of distortions.

Table 2 summarizes the deviations measured at the extremities of lacings and the main chord during the subsequent stages of welding.

*Table 2. Deviations (mm) at extremities of the tubes during sequential stages of welding.*

| **Stage of welding →** | | | **Expected coordinates (from CAD)** | **First Lacing tacked on main chord (initial set-up)** | **First Lacing welded and second lacing tacked** | **First two lacings welded and third lacing tacked** | **First three lacings welded and fourth lacing tacked** | **All four lacings welded to main chord** | **Absolute deviation from the first measurement** | **Magnitude of total deviation[1]** |
|---|---|---|---|---|---|---|---|---|---|---|
| **No. of points measured →** | | | ------- | 6,408 | 7,001 | 3,677 | 7,774 | 12,916 | --------- | --------- |
| **Coordinates of extremities** | **Main Chord (A10)** | X | -2700 | -2697.999 | -2698.874 | -2698.276 | -2698.373 | -2698.373 | 0.374 | 0.916 |
| | | Y | 0 | 1.821 | -1.146 | 0.555 | 1.230 | 1.232 | 0.589 | |
| | | Z | 0 | 4.493 | 3.810 | 4.332 | 3.899 | 3.899 | 0.594 | |
| | **First Lacing (H11)** | X | -1350 | -1351.008 | -1352.103 | -1349.156 | -1348.683 | -1348.683 | 2.325 | 2.916 |
| | | Y | 0 | -0.000 | -0.261 | -0.551 | -0.675 | -0.075 | 0.075 | |
| | | Z | 1203.2 | 1165.287 | 1163.621 | 1163.520 | 1163.529 | 1163.529 | 1.758 | |
| | **Second Lacing (H12)** | X | -510.118 | ------- | -519.025 | -519.104 | -519.144 | -519.144 | 0.119 | 4.001 |
| | | Y | 0 | ------- | 8.363 | 6.186 | 3.941 | 4.378 | 3.985 | |
| | | Z | 861.561 | ------- | 848.949 | 848.586 | 848.616 | 848.614 | 0.335 | |
| | **Third Lacing (C12)** | X | -588.808 | ------- | ------- | -516.504 | -517.650 | -517.650 | 1.146 | 1.628 |
| | | Y | -508.494 | ------- | ------- | -454.512 | -454.070 | -453.716 | 0.796 | |
| | | Z | 780.840 | ------- | ------- | 684.785 | 685.390 | 685.624 | 0.839 | |
| | **Fourth Lacing (C11)** | X | -1350 | ------- | ------- | ------- | -1342.025 | -1342.025 | 0 | 0.595 |
| | | Y | -667.414 | ------- | ------- | ------- | -640.267 | -639.772 | 0.495 | |
| | | Z | 1001.124 | ------- | ------- | ------- | 959.391 | 959.721 | 0.330 | |

## 5. CONCLUSIONS

Table 2 shows that at the completion of all welding, the chord had virtually no distortion at all of any significant nature. The other extremity of the main chord moved only by 0.916 mm – a deviation which lies within the error range of the CMM. The greatest final deviation (or misalignment) seems to be in the second lacing, of the magnitude of about 4 mm. These deviations would virtually have no effect on the joint, apart from an extremely miniscule effect on the strength and overall load-bearing ability of the joint due to additional constant residual stresses at the weld. It would be prudent to determine a method of providing better control in the workshop (and so in the field) in setting up the lacing tubes. A variable jig would be one way of controlling the variations encountered in setting up the cluster. However, such a jig-enabled control system is literally impossible to be set up in the field during the *in situ* manufacturing of a dragline.

This paper reported the numerical measurements of welding induced distortions in a 4-lacing dragline cluster (designated A11) in a workshop setting simulating as closely as possible the exact parameters of the GMAW process from the field welding of the actual dragline boom. Extraneous conditions like pressure, ambient temperature and relative humidity level of the surrounding air in the field and the dexterity of workmanship cannot be simulated in the workshop setting. Nevertheless, it can safely be concluded that welding induced distortions are extremely miniscule vis-à-vis the huge size of the tubular cluster and the overall dimensional inaccuracies generated by the welding process can be ignored in the design and analysis of dragline clusters.

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[1] Total deviation $|\delta| = \sqrt{\delta_x^2 + \delta_y^2 + \delta_z^2}$

## 6. ACKNOWLEDGEMENTS

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