THE EFFECT OF INNER DIAPHRAGMS AND CONTINUOUS SILL SECTION ON THE STIFFNESS OF AUTOMOTIVE B-PILLAR

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ABSTRACT

This paper discusses in detail on the behaviour of T-frame under specific loading obtained experimentally to investigate the deflection of the vehicle B-pillar. A series of T-frame were designed with inner diaphragm at various location in the sill member in order to investigate the effect of inner diaphragm and non-continuous closed hat section in the sill member. These two types of specimens were employed to show the effects of different types of sill member on the stiffness of the overall structure. The finite element analysis and experimental test were carried out on the in-plane bending. The experimental results were compared with the finite element analysis results to demonstrate the effectiveness of the inner diaphragm in the automotive B-pillar. Based on the results obtained from the experimental work, location of baffles for the specimens do not gives any major influences for in-plane bending case due to the shape and direction baffles are not suitable. From the results, the specimen with baffles located at the weld line is stiffer than the other specimens.

KEYWORDS

Vehicle T-frame, inner diaphragm, continuous closed hat section, experimental methods, finite element analysis

1. INTRODUCTION

The framework of the automotive body structure is comprised of thin walled section members in the formed of overlapping sheet metal fastened by spot-welds. In analysing the structure of the vehicle body, it is assumed that the intersecting angles at which member are joined together, varies according to the external forces. The automotive frame joints are subject to dynamic and static loads. The dynamic analysis can be carried out using matrix methods provided the overall stiffness. The mass distribution is known but it is difficult to find a suitable approach for damping properties. However, damping effects are less than inertia and stiffness effects. The static analysis can be used to find the force-displacement relationships of the frame joints. Static analysis in general includes the calculation of deformations and internal forces such as bending moments, torques, bi-moments, longitudinal and shear forces. Experiments and finite element analysis can be used to determine joint rigidity. Although this framework is accounting for only a small part by weight of the entire vehicle but it exert a substantial effect on the response of the vehicle structure.

The effective design of the vehicle T-frame will maximise the safety of the passengers and reduce the vehicle weight. The automotive industries have been working hard to reduce the vehicle weight in order to achieve better fuel efficiency and to reduce global environmental problems. Furthermore, in improving the safety of passengers in a collision, it will be benefit to decrease the maximum load that occurs during the collision. This can reduce the level of occupant's injury and control the deformation of the structure to ensure a sufficient safe space for occupant [9].

Therefore, in order to reduce the vehicle body weight and simultaneously maintaining satisfactory function, performance and engineering reliability, it is extremely important to establish a consistence procedure in analysing and evaluating the frame joint behaviour. Noted that, although the frame joints are only a small part of the entire vehicle, they exert a great influence on the structure system.

The goal of this work is to evaluate the designed of inner diaphragm into the automotive T-frame at several location on continuous sill member. The specimens were employed to show the effects of different location of baffles and in continuous sill member on the stiffness of T-frame structure. A special mechanical test rig was designed and manufactured in order to test the T-joint. Experimental test and finite element analysis were carried out. The results obtained were analysed.

2. RELATED WORK

There have been numerous researches involving joint stiffness of the automotive body structure related to thin-walled structures in which the studies are on fastened method, flexible characteristics, collapse behaviour, torsional problems and stress distributions. These studies were conducted since the frame joints give a very important affect on the vehicle response. Moreover, most of the studies found that the stiffness of the frame joints greatly influenced on the overall stiffness of the vehicle body structure.

McGregor et al. [1] developed a joint design approach for adhesively bonded and spot welded aluminium automotive structures. The approach includes an allowance for joint geometric variables, manufacturing variability and complex joint loading. An important aspect in the development of the approach to minimise the detail required to model the joints in a full vehicle model. The accuracy of the approach is demonstrated on a simple structure subjected to complex loading, and the use of the approach is illustrated on a full vehicle.

Sunami et al. [2] performed their analysis on the joint rigidity of the automotive body structure both in-plane and out-of-plane bending of plane joint structures. They have made a fundamental study of the joint rigidity involving T or L shaped thin walled box beams and examining several factors that caused the rigidity to be reduced. In their work, they used a theoretical equation; i.e. the theory of shear flow and the results confirmed by experimental values. For the in-plane study, they have concluded that the joint rigidity of box beams depends on the "release" (insufficient constrained condition) and shearing deformation and elongation of joints. From this study the analysis of fundamental behaviour of joints can be used as a step to plan structural designs. Sharman et al. [3] did a comprehensive study on the effect of local detail on the stiffness of car body joint. Three joints between the structural members meeting the roof of a small car were tested for stiffness in the plane of the side frame.

Niisawa et al. [4] conducted an analytical method of rigidities of thin-walled beams with spot welding joints and its application to torsion problems. In their study, they have discussed the elastic properties of the spot welding joints in the transmission of the shearing forces and developed the method based on shear flow theory in introducing the elastic properties of spot welding joints into the structural analysis of thin-walled beams. Based on this study, they found that the welding point at the middle station transmits the maximum shearing forces and the torsional rigidities not only depend on the length of beams but also on the pitch of welding points.

Ishiyama et al. [10] did a study on the collapse behaviour of thin-walled beams under torsional moments. The collapse tests were made a square and rectangular section tubes (closed section), a hat section beam closed by spot welding (semi closed section) and channel beams (open section). Based on the geometry of the cross sections and material properties of the beams, they have discussed the yield and maximum moments in the collapsing process and clarified the effect of constraints against warping deformation on yielding moment for the channel beams.

Vayas et al. [5] developed a method for calculating the carrying capacity and the deformation characteristics of the joints. Static and kinematics limit state models were presented which allow the ultimate strength to be determined from closed formulae.

For the finite element analysis, Shakourzadeh et al. [6] deals with the finite element formulation for the analysis of space frames. A numerical method is presented to take into account the deformation of the joint connections in linear, non-linear and stability analyses of three-dimensional thin walled beam structure. Moon et al. [7] presented a joint modelling methodology where the definition and assumptions of the joint are discussed. In addition, the joint stiffness analytical model is proposed using static load test results, also presented the sensitivity analysis method and a joint stiffness-updating algorithm. To verify these methods, the FE analysis results of a half size structural model of an automobile with rigid joints and rotational spring joints are compared with experimental analysis results. Farooque et al. [8] proposed the finite element formulation to incorporates rectangular plate and edge boundary spring elements. The model is then used to determine the punching shear and rotational stiffness of both double chord T-joints and single chord T-joints, thus demonstrating its versatility. The numerical values obtained are in good agreement with the experimental results available in the literature.

3. FUNDAMENTAL ASPECT OF THE SPECIMEN

The specimens were made of cold rolled mild steel. It is consisted of five components, which are the base plate, inner diaphragm (baffles), vertical member, horizontal member (sill) and the jointing member. Once constructed, it formed a T-joint member with 75mm corner radius at the jointing area and with closed hat section members and spot welded along its flanges as shown in Figure 1.

The base plate was a planar sheet with 1.2mm thickness in the form of T-shape with 55mm corner radius. The horizontal member is an open hat section with 20mm flanges over the complete length and having the same thickness as the base plate. It is connected to the base plate by means of spot welds at the pitch distance of 50mm. Before these two components are connected, the inner diaphragms are connected to their particular locations in the horizontal member by means of three spot welds at two equal pitches all the way round except the one that faces the base plate. This has been plug welded at two equal distances with the base plate. The purpose of having these holes and extension length is to build a box of cement block at each end so that it can be regarded as fixed ends.

The vertical member is connected to the base plate by means of spot welds. This assembly is connected to a connecting plate with dimensions of 180mm X 180mm X 10mm at the top part of the assembly by means of $C0_2$ arc welding. The purpose of having the connecting plate is to ensure that the vertical member will move as one entity when loads are applied.

The jointing member connects the base plate, vertical or horizontal member by means of spot welds, fillet welds, plug welds and $C0_2$ arc welds. Plug welds were used in any area where spot welding electrodes were not accessible due to the shape of the T-joint. Although the jointing member was designed as a single piece, in real case it was made from three pieces of steel which are joined by one $C0_2$ arc welding operation due to the lack of production tools. In production cars the hat section of the sill and 'B' post are formed as one pressing. In this attempt, the work tried to simulate this without the facilities of press tools.

3.1 Specimen Design

In this work, the specimen have been constructed with three parts which used a continuous sill member. The inner diaphragms have been located in-line with the sides of B-pillar (AM1), at the weld line (AM2) and at the outside of the weld line (AM3). The detailed of the specimen is shown in Table 1. Figure 1 shows the parts of the specimen.

Table 1 Specimen types: Continuous Horizontal Member.

Specimen's Identity	AM1	AM2	AM3
Location of Baffles (Left and Right)	160 mm	272 mm	40mm

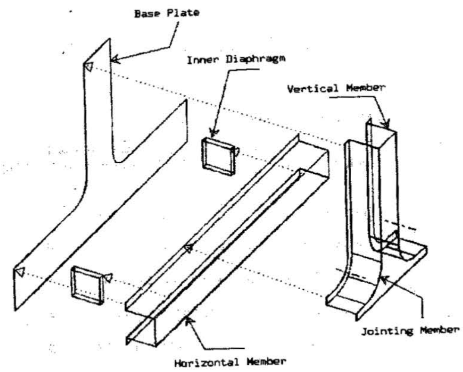

Figure 1: Parts of specimen

3.2 Experimental

The In-plane bending case was considered in the experimental testing. The load applied at the top part of the vertical member and in parallel with the horizontal member as shown in Figure 2, Figure 3 and Figure 4. The total displacement can be written as:

$$\delta_t = \delta_{VW} + \delta_{HW} + \delta_{HM} \quad (1)$$

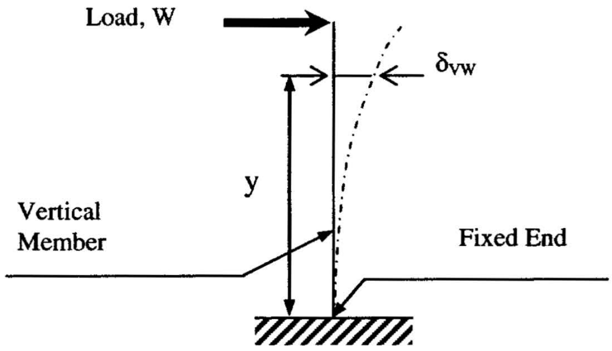

Figure 2 Vertical member as a cantilever

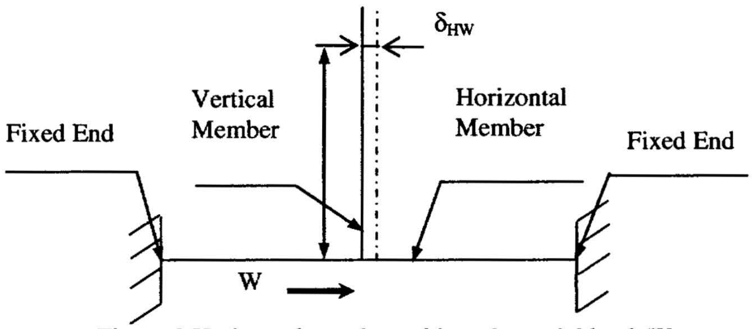

Figure 3 Horizontal member subjected to axial load, W

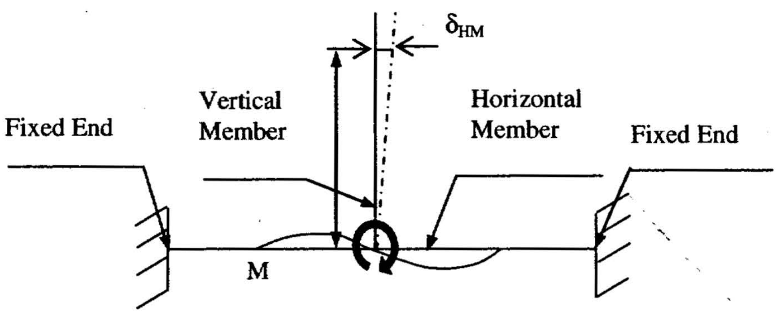

Figure 4 Horizontal member subjected to bending moment

Introduction of these rotational assumptions, the experimental and finite element analysis of the stiffness of the joint can be easily obtained. From experimental test, the total displacement can be measured, while the displacement of each member due to deformation of a beam can be calculated using beam theory or finite element analysis. In addition, the displacement at the loading point can be incorporated in function, which includes the angular stiffness of the joint.

To conduct the in-plane experimental testing, a mechanical test rig was designed and manufactured. The test rig was built to be flexible and accurate. The test rig was equipped with tensile gauge, turnbuckles, a clamping set, Dexion frame and dial gauges.

4. RESULTS

In-plane bending, 4 interest points were measured at the specimen. These points were labelled by W, X, Y and Z (see to Figure 5). Figure 6 shows the in-plane bending experiment on the test rig.

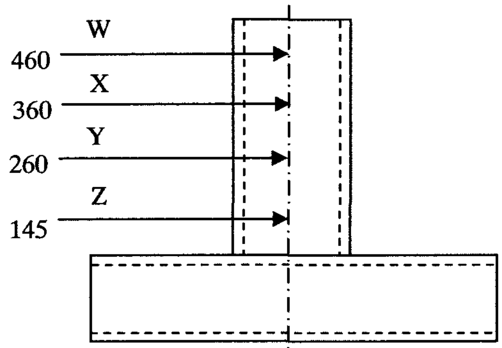

Figure 5 Location of points for experimental testing.
(All dimensions in mm)

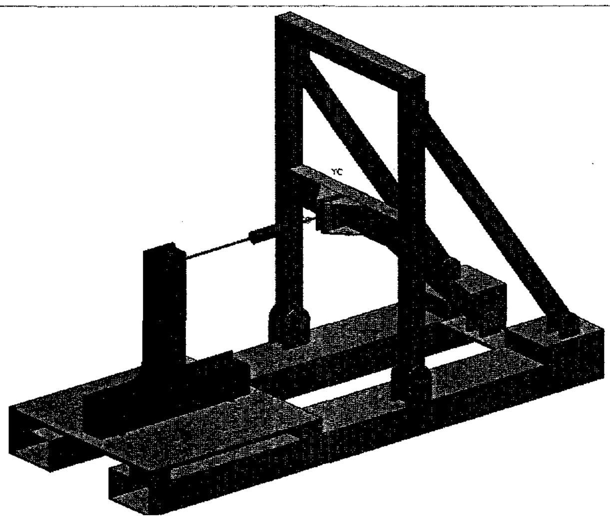

Figure 6 The in-plane bending experiment on the test rig

4.1 In-Plane Bending Test Result for Specimen AM1

Specimen AM1 is a continuous sill member with the baffles located at the weld line i.e. 160 mm left and right from the centreline of the T-joint. The linear of displacement with load occurred at point W, X, Y and Z is shown in Figure 7.

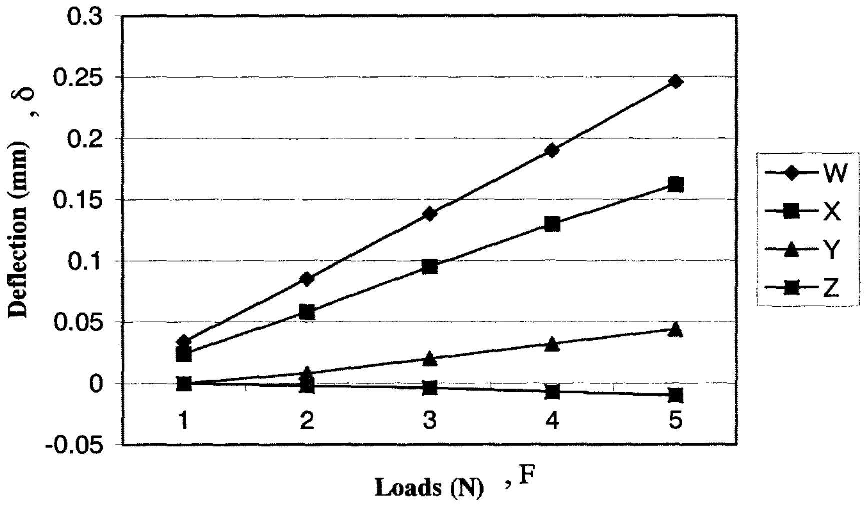

Figure7 Deflection vs. load (Linearity Displacement)

4.2 In-Plane Bending Test Result for Specimen AM2

This specimen is a continuous sill member with the baffles located at the outside of the weld lines i.e. 272mm left and right from the centreline. The experimental results for AM2 as shown in Figure 8. Figure 8 show the deflection versus distance (location), where it is constructed based on maximum load applied.

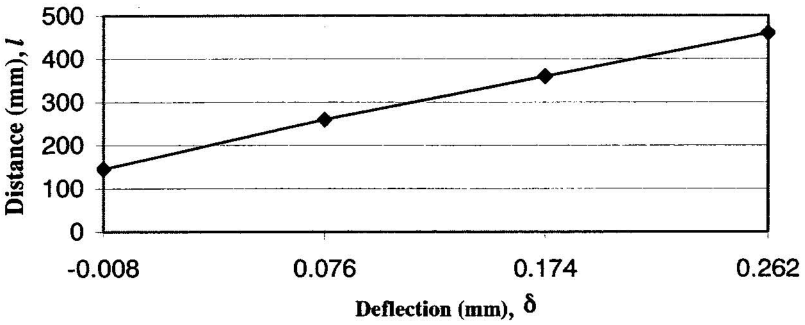

Figure 8 Distance vs. Deflection (AM2)

4.3 In-Plane Bending Test Result for Specimen AM3

The specimen is a continuous sill member with the baffles located in-line with the vertical member, i.e. 40mm left and right from the centerline. he experimental results for AM2 as shown in Figure 9. The graph of deflection versus distance (location) is constructed based on the maximum load applied. Figure 9also shows that negative displacement existed at the joint region, i.e. point Z. This is the bowing effect due to compression.

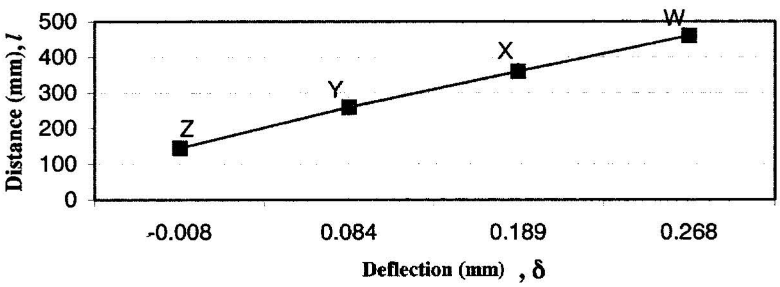

Figure 9 Distance vs Deflection (AM3)

4.4 Deflection of Vertical Member and Joint Region of Continuous Sill Member

The results obtained based on 900 N longitudinal load to specimen Type 1 can be seen in Table 2 and Figure 10.

Table 2 Deflection of vertical member and joint region Type 1

Specimen	Location (mm)			
	W (460)	X (360)	Y (260)	Z (145)
AM1	0.246	0.162	0.044	-0.010
AM2	0.262	0.174	0.076	-0.008
AM3	0.268	0.189	0.084	-0.008

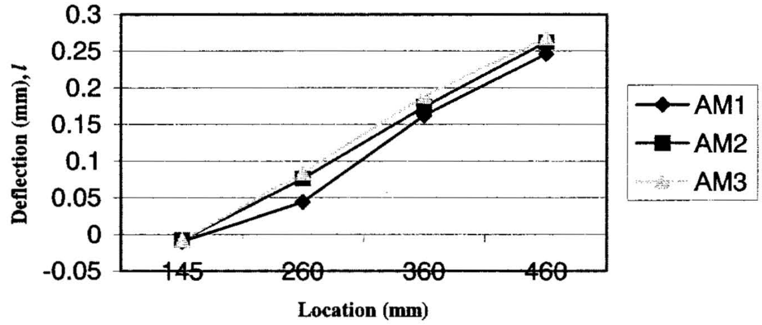

Figure 10 Deflection of vertical member and joint region of continuous sill member (Unit: mm)

Based on Table 2 and Figure 10, it suggested that,

a. Location of baffles on a continuous sill member does not give any major influence on the in-plane bending case. However, among these specimens, the specimen with baffles located at the weld line is stiffer than the baffles located with the side of B-pillar.

b. No matchbox effect occurred in these types of specimens.

5. FINITE ELEMENT ANALYSIS

The modelling of the specimen has been carried out to simulate the actual joints of a vehicle. The entire finite element (FE) consisted of four main parts i.e. base plate, vertical member, horizontal member and inner diaphragm (baffles) were modelled. The model was created using square corner (i.e. no corner radii) in order to reduce the process time.

The model were constructed using thin shell element without considering the solid modelling since the thickness of the plate is 1.2mm which thin enough to neglect the thickness effect. A mapped meshed were used throughout the construction of the model in order to get better accuracy. Moreover the model is free from irregular shape. A four nodded simple rectangular elements were used for mapped the meshing.

The top surfaces of the vertical member were constrained using rigid element so that it can be moved as a unit when the loads were applied. The base plate and both vertical member and horizontal member were connected by means of beam element (representing spot welds) at the pitch distance of 50mm. The inner diaphragm are connected to their particular location in the horizontal member by means of three beam elements at two equal pitches all the round. Both ends of the horizontal member were fully restrained from any degree of freedom, which represent as fixed ends. Two point forces were located along the edge (on the nodes) of the top surface of the vertical member (i.e. facing the direction of the force). 900 N forces were used for in-plane bending case. The longitudinal force of 900 N was applied at the top of the vertical member.

5.1 Finite Element Results

For the Finite Element (FE) analysis, the locations for the measurement are quite similar to the location in manual testing. The locations for measurement were slightly deviates from because the location of the nodes is quite difficult to be on the same position. In this Finite Element (FE) analysis, tolerance of ±5mm has been given for the locations of the measurement.

Model AM1

The results obtained from the FE analysis are shown in Figure 11. The deformed model is shown Figure 12. It can be seen that the joint region of the vertical member and the centre region of the horizontal member were largely deformed.

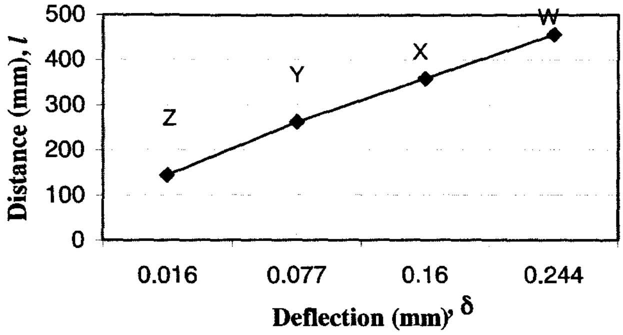

Figure 11 Deflection versus distance (AM1)

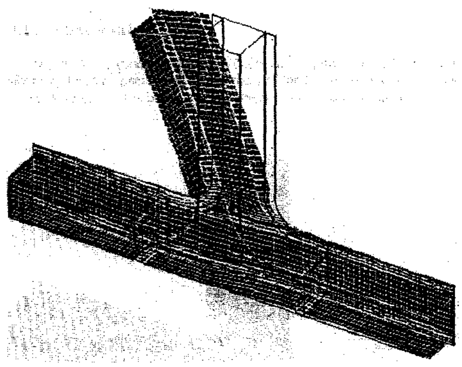

Figure 12 Stress distribution for model AM1

Model AM2

The stress distribution appeared in model AM2 is quite similar to AM1 when longitudinal of 900N was applie(the top of the vertical member. The results as shown in Figure 13, the graph shows no negative displacem occurred and therefore no occurrence of local bending at the particular point of measurement. High stress appea to be along the flanges at the corner radii region.

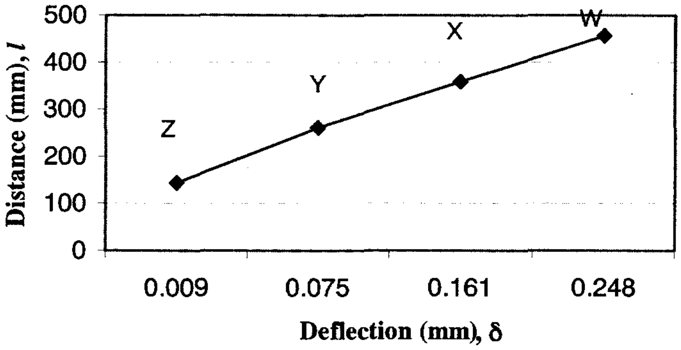

Figure 13 Deflection versus distance (AM2)

Model AM3

The results obtained from FE analysis for AM3 are shown in Figure 14. The stress for AM3 is concentrated along the flanges in the corner radii region. The model AM3 have baffles located in-line with the vertical line, therefore it prevents the model from being largely deformed at the center region. However, it starts deformed immediately after the right baffle.

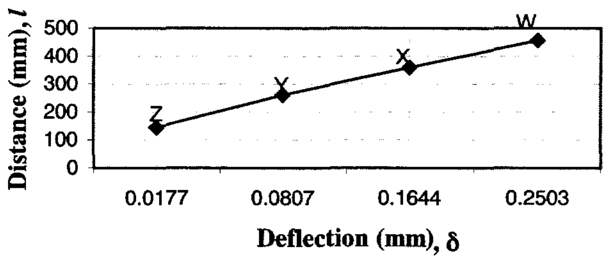

Figure 14 Deflection versus distance (AM3)

5.2 Deflection of Vertical Member and Joint Region of Continuous Sill Member

The results obtained based on 900N longitudinal load applied to T-flames in FE analysis are presented in Table 3 and Figure 15.

Table 3 Deflection of vertical member and joint region (Unit: mm)

Location	W	X	Y	Z
AM1	0.244	0.160	0.077	0.016
AM2	0.248	0.161	0.075	0.009
AM3	0.250	0.164	0.081	0.018

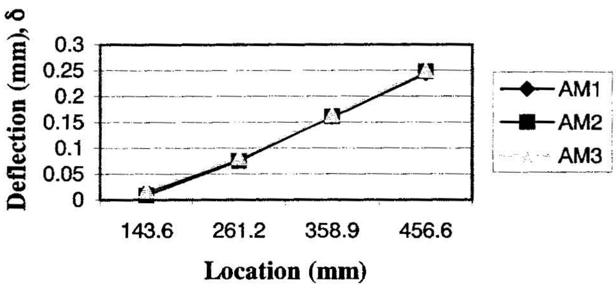

Figure 15 Deflection of vertical member and joint region of continuous sill member (Unit: mm)

Based on Table 3 and Figure 15, the following are the pre-conclusion that can be drawn.

a. Model AM1 is stiffer than the other two models. However as the locations of measurement is nearer to the joint area, model AM2 shows that it is the stiffest among the models
b. No 'match box' effect occurred.

6. CONCLUSIONS AND DISCUSSION

The results obtained from experimental analysis and finite element analysis is shown in Table 4.

Table 4 Displacement of vertical member due to longitudinal load of 900N

Location	Experimental Test			Finite Element Analysis		
	AM1	AM2	AM3	AM1	AM2	AM3
W	0.246	0.262	0.268	0.244 (99%)	0.248 (95%)	0.250 (93%)
X	0.162	0.174	0.189	0.160	0.161	0.164
Y	0.044	0.076	0.084	0.077	0.075	0.081
Z	-0.010	-0.008	-0.008	0.016	0.009	0.018

From Table 4, it can be seen that the results obtained from FE analysis gave deflection within the range of 93% to 99% of the experimental test. The results are acceptable; however, if the quality of the specimens were good (experimental test) or if the 'arc welding' were considered at the joint region in FE analysis, the results might be in good.

There are differences of the results in both analyses especially at point Z. From FE analysis, there are no negative displacement occurred at point Z (i.e. no occurrence of local bending). These results seem to be contradicted with the results obtained from the experiment test but the reason can be found in the quality of the specimens. In the experimental test, the specimens have undergone an arc welding operation, which might have reduced the strength of the specimen at the joint region. The results show that specimen AM1 is stiffest model and AM2 is stiffer than AM3. The results show that spot welds are far from yield stress and there do not give major influences on the experimental test.

Based on the results obtained from the experimental work, location of baffles for the specimens has no influences for in-plane bending case due to inappropriate shape and direction baffles. However, the specimen with baffles located at the weld line is stiffer than the other specimens.

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