THE STATIC BEHAVIOR OF SPATIALLY LOADED THREE DIMENSIONAL MULTIPLANAR RECTANGULAR HOLLOW SECTION JOINTS

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Considerable research in the field of the ultimate behavior of simple uniplanar joints has been undertaken in the past three decades. However for multiplanar joints in hollow sections, experimental or numerical results are very scant. In order to get an insight into the static behavior of such joints, a finite element model is developed and applied to hollow section joints to evaluate the elastic stiffness of the joints. Nine multiplanar joints have been studied in this paper. The analyzed joints are subjected to spatially loads resulted from the global analysis of any structure contains these joints. The elastic stiffness of the joints has been calculated for different geometrical parameters and under different sets of loads in order to evaluate the behavior of multiplanar joints clearly. The multiplanar effect on the behavior of the joints is studied and compared with the behavior of uniplanar joints. Also, comparisons between the experimental work obtained in this field and the numerical results calculated in this analysis are done.

فى هذا البحث تم عمل نموذج نظرى ثلاثى الأبعاد باستخدام طريقة العناصر المحددة لحساب جساءة الوصلات متعددة الاتجاهات والمكونة من قطاعات مستطيلة مفرغة تحت تأثير مجموعة من الأحمال الفراغية المختلفة. تم أيضا" دراسة تأثير كلا" من العوامل الهندسية المختلفة وتأثير تغير الشروط الحدية لنهايات للضلع خارج المستوى.

تم أيضا" عقد مقارنات بين قيم الجساءة المحسوبة للوصلات متعددة الاتجاهات وبين الوصلات ذات الاتجاه الواحد لدراسة تأثير تعدد الاتجاه على قيم الجساءة. كذلك تمت مقارنة النتائج مع مثيلتها من النتائج العملية والنظرية وأظهرت النتائج فروق مقبولة بين نتائج الأبحاث السابقة وبين النتائج التى تم الحصول عليها باستخدام النموذج النظرى المستخدم.

Keywords: Static Behavior, Hollow Section, Multiplanar Joint, Spatially loads, and Elastic Stiffness.

INTRODUCTION

The strength of uniplanar tee and cross joints in Rectangular Hollow Sections (RHS) is given in various design recommendations in terms of the yield line solution [1], where the major parameters are the width ratio (b/B) and the chord slenderness (H/t). The experimental work described by Davies *et al.* [2] was designed to examine the effect of welding additional RHS branches to the out-of-plane chord faces of the Tee joints, and the variation of the stiffness and axial strength of the joint under various ratios of out-of-plane axial force. This formed part of a combined European investigation carried out with Delft (DX joints), and Corby (KK joints). It was also to form the basis of comparisons with Finite Element (FE) simulation of the joint behavior.

Earlier testing and Finite element work by Paul *et al.* [3] has indicated that a significant variation in the strength of a Circular Hollow Section (CHS) joint can take place due to the axial loading of out-of-plane members. However yield line modeling indicates that only modest enhancement occurs for RHS joints when loads are applied in the same sense [4]. The values allowed in codes of practice for CHS joints are indicated in Figure 1.

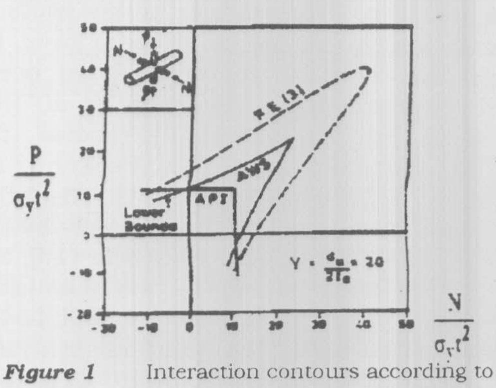

Figure 1 Interaction contours according to API, AWS

and FE [2]

The limitation on symmetry of the Tee joint (compared with the X joint), means that care have to be taken to define the freedom required at the outer end of each branch, due to the effect of unsymmetrical chord side wall distortion (Figure 2). The in-plane force normally produces a lateral deflection at the ends of the out-of-plane bracing (opbs), which under a compressive load could produce P/Δ instability effects as shown in Figure 2-b. Therefore, Davies *et al.* [2] decided to test the specimens in two ways:

1. with complete freedom of opbs (Figure 2-b).
2. with shear provided at the ends of opbs, such that these branches moved with the over-all movement of the chord (Figure 2-c).

A comparison of the rigidity of the three dimensional joints is presented for both modes of testing in terms of the rigidity of the uniplanar joint.

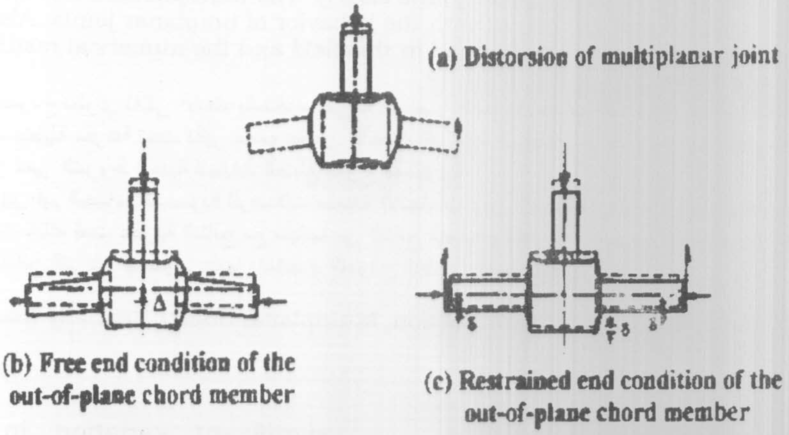

Figure 2 Effect of out-of-plane chord member end restraint [2]

SPATIALLY LOADS

The analyzed multiplanar joints are subjected practically to several forces resulting from the analysis of the structural system used in. Rectangular hollow section uniplanar joints loaded by an axial force, P, through the vertical member have been studied experimentally by Kato *et al.* [5], Korol *et al.* [6], Zhao *et al.* [7], Yu *et al.* [8], Zhao, [9], Partanen *et al.* [10], Packer, [11], Zhao *et al.* [12], and Zhao, [13]. Also, the joints have been studied theoretically by El-Hifnawey, [14], Zhao, and Hancock, [15], Yu *et al.* [8,16], Lu *et al.* [17], Soh *et al.* [18], Korol *et al.* [19], and El-Heweity, [20]. In all of these researches, the joint is analyzed under a normal force coming from the branch member (axial force) only, although, the axial force is not the only force acting on the joint.

In this study, the spatially loads are the straining actions acting on the in-plane and out-of-plane chord members and the vertical member at the cutoff sections of any structure having these joints. These loads (straining actions), shown in Figure 3, are normal force and bending moment acting on the in-plane and out-of-plane chord members together with the axial force acting through the vertical member. The effect of these loads on the rigidity of the joint is studied.

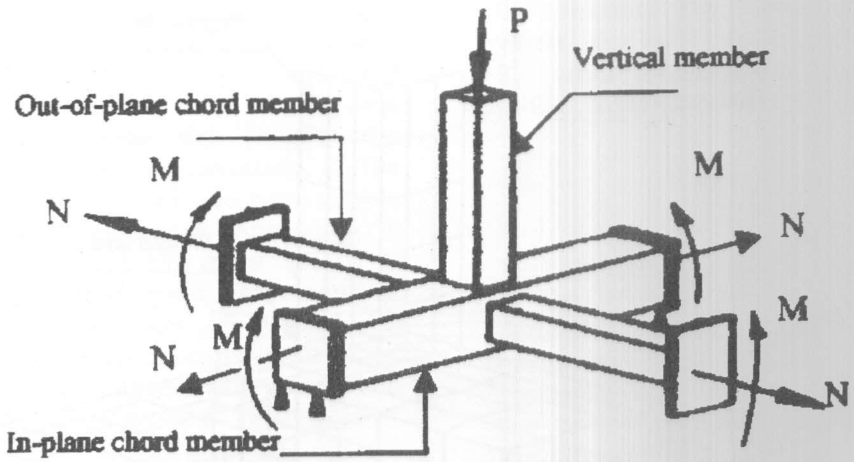

Figure 3 Spatially loads on multiplanar joint

MODELING OF MULTIPLANAR JOINT

The behavior of multiplanar joint is simulated by a three dimensional model. Using geometrical and load symmetry, one quarter of the joint has been modeled. In order to carry out this research, the finite element program COSMOS is employed [21]. Figure 4 shows the finite element mesh with boundary conditions used for multiplanar joints. In this model, two rollers are placed at the ends of the chord members in order to separate the influence of bending moments acting on the chord members from the axial force applied through the vertical member. The two rollers are placed at the transition of the rounded corner portion to the flat plate of the chord member to isolate the localized joint behavior from chord member bending. A corner radius $r = 1.5t$ is assumed as indicated in the British and Australian standards for the cold formed sections with thickness greater than 4 mm.

For the analyzed joints, the loaded chord span is an important parameter where the failure mode of the joint can vary from local deformation failure for short spans to general flexural plastification of the chord for longer spans. So, the length of the in-plane and out-of-plane chord member is taken 2H+h as considered in Kato *et al.* research work [5]. Where, H is the depth of the chord member, and h is the depth of the vertical member.

In the analysis of the multiplanar joint, it is assumed that the vertical member behaves as a beam column. Furthermore, the top flange plate of the chord member within the inclusion is presumed to undergo only rigid body type translation, δ, under axial force, P. This is so because of the stiffening effect provided by the periphery of the vertical member. The bending moments, M, at the ends of both the in-plane and out-of-plane chord members are simulated by two equivalent normal forces, N_{eq}, acting at the ends of the two chord members. These equivalent normal forces are equal to the bending moment, M, divided by the depth of the chord member, H.

$$N_{eq.} = \frac{M}{H} \qquad (1)$$

The in-plane chord normal force, N, or N_{eq} is distributed as a line load along the perimeter of the ends of the chord cross-section (Figure 5). In order to achieve this distribution, the elements at the ends of the chord member are assumed to be very stiff compared to the other elements.

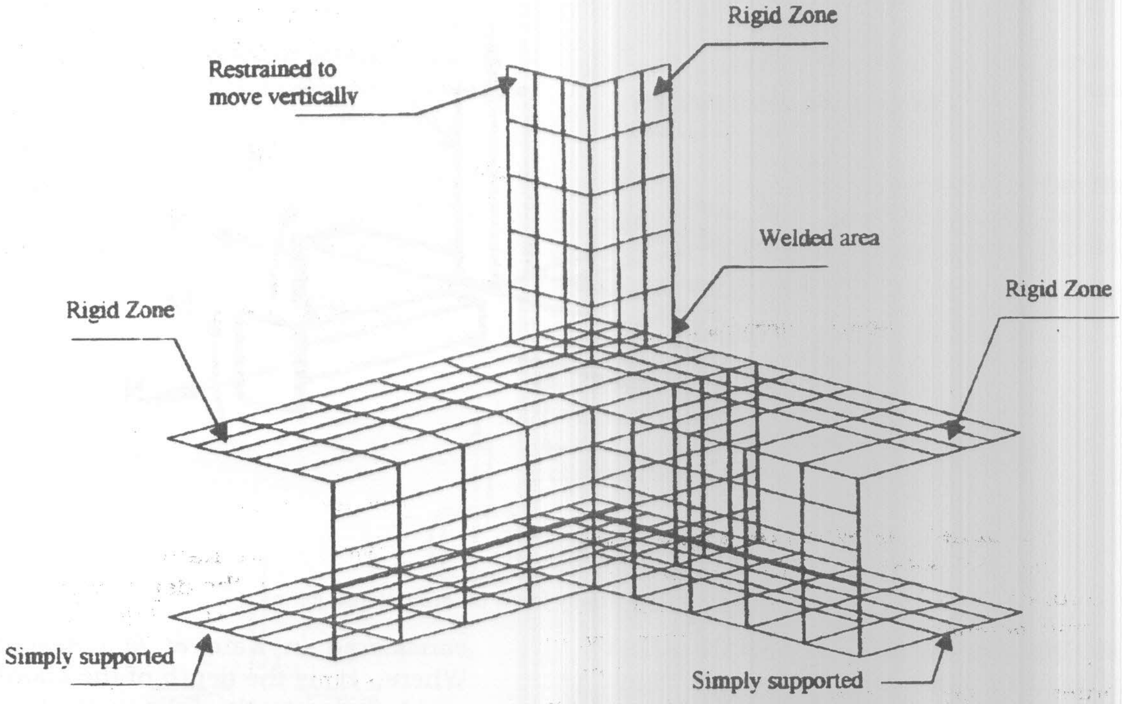

Figure 4 Finite element mesh of quarter of the multiplanar joint with boundary conditions

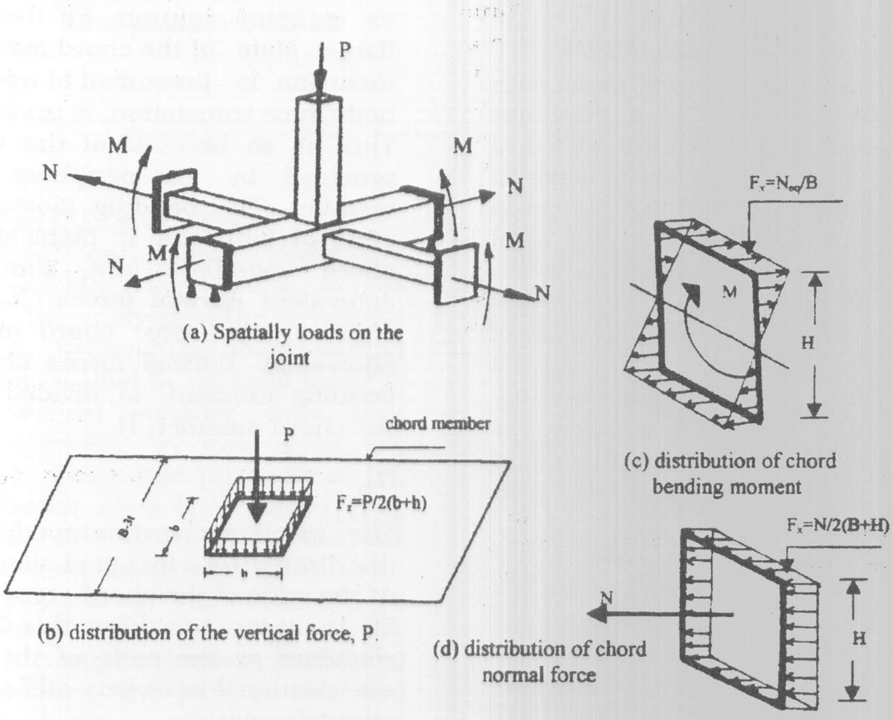

Figure 5 Load distribution on the multiplanar joint

A so-called conservative equivalent weld thickness is used in order to model the fillet weld. It is found that when weld modeling is excluded, much lower strength and stiffness values are obtained than when the weld modeling is included. As the weld dimensions vary along the length, the mechanically equivalent magnitude of the weld has to be used when the weld area is modeled with shell elements. According to Koning *et al.* [22] and Yu *et al.* [8], it is concluded that either good agreement or conservative results are obtained in comparison to the experimental results, by choosing the conservative equivalent weld thickness as shown in Figure 6, i.e.

$$t_w = \frac{0.5\ (a_v x a_h)}{\ell} \qquad (2)$$

where, t_w is the thickness of weld

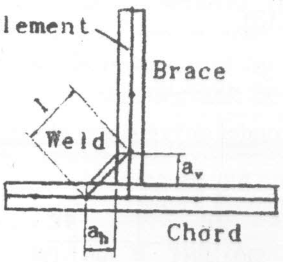

Figure 6 Average thickness of fillet we'd t_w

ELASTIC STIFFNESS (S)

It is defined as the slope of the load-deformation, P-δ, curve in the elastic region when the joint is subjected to an axial force, P, while δ is the corresponding joint deflection (Figure 7). i.e.,

$$S = \frac{P}{\delta} \qquad (3)$$

To calculate theelastic stiffness of the joint, S, the joint is forced to undergo a constant deflection, δ, at all the nodal points on the perimeter of the inclusion. The corresponding values of the shear forces and the moment are calculated in order to obtain the force, P, as

$$P = 4\left[\int_0^{b/2} Q_x dy + \int_0^{a/2} Q_y dx + R\right] \qquad (4)$$

where,
$R = -2\ M_{xy}$, Q_x and Q_y are shear forces per unit length in x and y direction respectively and R is the corner force.

A sketch plan for the inclusion showing the internal forces used to determine the applied axial force, P, around the inclusion is given in Figure 8.

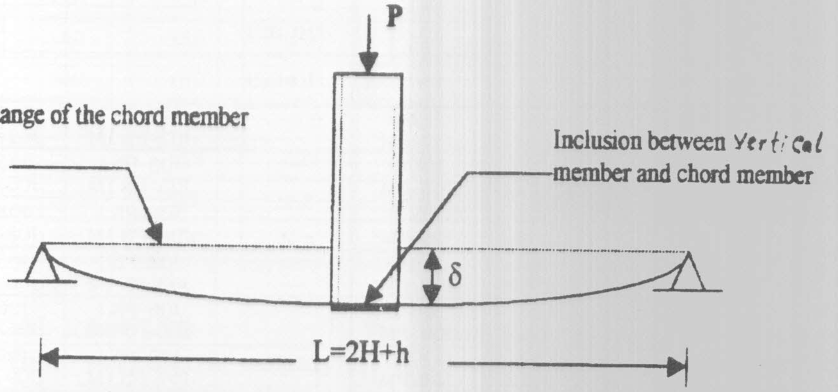

Figure 7 Hollow section joint undergoing rigid body mode deflection at the inclusion

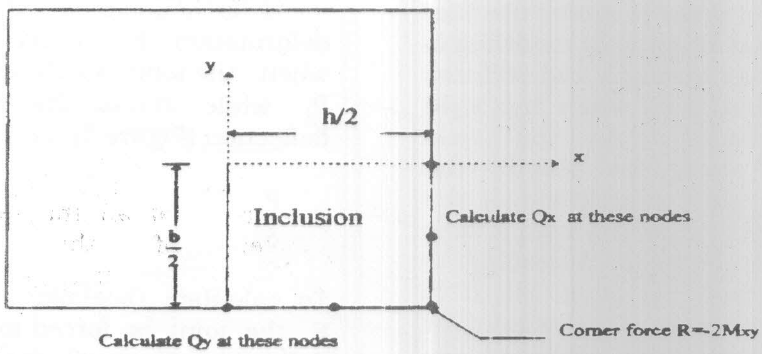

Figure 8 Sketch plan for the position of internal forces used to determine the applied axial force, P.

PARAMETRIC STUDY

In this study, ten joints, named in the research program J01to J10, are analyzed in case of multiplanar joints. Table 1 shows the research program for all joints analyzed. The geometrical parameters of these joints are varied in order to study the effect of the geometrical parameters on these joints. The joint parameters of the numerical models are the width ratio, b/B, (b/B=0.5, 0.6, 0.8, and 1.0), chord slenderness, H/t, (H/t=15, 23.8, 25, and 35).

Table 1 Multiplanar joints with different geometrical parameters and under different sets of spatially loads.

H/t	End condition of out-of-plane member	b/B	M	N				
				0.0	0.56P	2P	4P	6P
15	Simply supported	0.5	0.0 1.6M	J01-P J01-PM	-	J01-PN1 J01-PN1M	J01-PN2 J01-PN2M	J01-PN3 J01-PN3M
		0.8	0.0 1.6M	J04-P J04-PM	-	J04-PN1 J04-PN1M	J04-PN2 J04-PN2M	J04-PN3 J04-PN3M
		1.0	0.0 1.6M	J07-P J07-PM	-	J07-PN1 J07-PN1M	J07-PN2 J07-PN2M	J07-PN3 J07-PN3M
23.8	Simple support end	0.6	0.0	-	J10-SSP	-	-	-
	Free end			-	J10-SFP	-	-	-
	Restrained			-	J10-SRP	-	-	-
25	Simply supported	0.5	0.0 1.6M	J02-P J02-PM	-	J02-PN1 J02-PN1M	J02-PN2 J02-PN2M	J02-PN3 J02-PN3M
		0.8	0.0 1.6M	J05-P J05-PM	-	J05-PN1 J05-PN1M	J05-PN2 J05-PN2M	J05-PN3 J05-PN3M
		1.0	0.0 1.6M	J08-P J08-PM	-	J08-PN1 J08-PN1M	J08-PN2 J08-PN2M	J08-PN3 J08-PN3M
35	Simply supported	0.5	0.0 1.6M	J03-P J03-PM	-	J03-PN1 J03-PN1M	J03-PN2 J03-PN2M	J03-PN3 J03-PN3M
		0.8	0.0 1.6M	J06-P J06-PM	-	J06-PN1 J06-PN1M	J06-PN2 J06-PN2M	J06-PN3 J06-PN3M
		1.0	0.0 1.6M	J09-P J09-PM	-	J09-PN1 J09-PN1M	J09-PN2 J09-PN2M	J09-PN3 J09-PN3M

The spatially loads acting on the joints are taken as ratios from the axial force, P, acting through the vertical member. The ratio between the chord tensile force and the axial force is taken (N= 0.0, 2P, 4P, and 6P) and the ratio between the chord moment and the axial force is taken (M= 0.0, and 1.6M meter).

The joint, named in the research program J10, is analyzed in order to compare between the results calculated by using the proposed model and the experimental and theoretical results done by Davies *et al.* [3] and Yu *et al.* [8] respectively. In the experimental and theoretical work compared with, the joint is analyzed with fixed geometrical parameters (b/B= 0.6, L= 875 mm, and H/t 23.8). For this joint, three different boundary conditions for the ends of the out-of-plane chord member are considered. First, simple supports are placed at the ends of the out-of-plane chord member, second the out-of-plane chord member has a free end, and third the member is restrained by end shear to ensure that the member will be remained parallel as it moved with the in-plane chord member. The two later boundary conditions are used in the experimental and theoretical work done by Davies *et al.* [3] and Yu *et al.* [8], so a comparison is done between the three different boundary conditions. Only a normal force with value equal 0.56P is acted on the out-of-plane chord member which means that the effect of both the normal force and the bending moment acting on the in-plane chord member is neglected.

CHARACTERISTICS OF JOINTS USED

The nominal dimensions of the multiplanar joints analyzed are tabulated in Table 2 with an assumed corner radius r =1.5t. The height of the vertical member of the joint is taken equal to 3h (three times the depth of the vertical member)[5]. The material properties of the chord members and the vertical member are the same and they are of steel of grade 37 with yield stress, σ_y=240MPa and modulus of elasticity, E=2.1×10^5 MPa.

Table 2 Nominal dimensions of the joints

Joints	In-plane and out-of-plane Chord Member (mm)			Vertical member (mm)			Length of Chord (mm)
	H	B	t	h	B	t_1	
J01	150	150	10.0	75	75	3.2	375
J02	150	150	6.0	75	75	3.2	375
J03	150	150	4.3	75	75	3.2	375
J04	150	150	10.0	120	120	3.2	375
J05	150	150	6.0	120	120	3.2	375
J06	150	150	4.3	120	120	3.2	375
J07	150	150	10.0	150	150	10.0	375
J08	150	150	6.0	150	150	6.0	375
J09	150	150	4.3	150	150	4.3	375
J10	150	150	6.3	90	90	6.3	875

NUMERICAL RESULTS

According to the parametric study discussed above, Table 3 shows the elastic stiffness of the multiplanar joints for different geometrical parameters and under different sets of spatially loads. From the results obtained, comparison with the work done before, the multiplanar effect, the effect of spatially loads acted on both the in-plane and out-of-plane chord members, and the effect of the geometrical parameters of the joints are discussed in the following sub-sections.

Table 3 Values of Elastic Stiffness, S, for the multiplanar joints with different geometrical parameters and under different load and boundary conditions.

H/t	End condition of out-of-plane member	b/B	M	S (kN/mm)				
				N				
				0.0	0.56P	2P	4P	6P
15	Simply supported	0.5	0.0	286.94	-	275.41	264.77	254.92
			1.6P	116.49		114.55	112.66	110.84
		0.8	0.0	896.86	-	791.90	708.94	641.71
			1.6P	147.45		144.30	141.29	138.40
		1.0	0.0	1975.11	-	1579.03	1315.27	1127.02
			1.6P	191.11		186.58	182.26	178.14
23.8	Simple support end	0.6	0.0	123.43	118.78	-	-	-
	Free end			104.50	96.32	-	-	-
	Restrained			115.26	111.36	-	-	-
25	Simply supported	0.5	0.0	81.17	-	79.49	77.88	76.33
			1.6P	50.00		49.36	48.73	48.12
		0.8	0.0	327.01	-	300.32	277.65	258.17
			1.6P	88.41		86.34	84.36	82.47
		1.0	0.0	1172.75	-	941.71	786.72	675.54
			1.6P	119.19		116.29	113.52	110.89
35	Simply supported	0.5	0.0	34.76	-	33.50	32.33	31.24
			1.6P	20.83		20.37	19.93	19.51
		0.8	0.0	160.49	-	136.72	119.09	105.49
			1.6P	39.30		37.69	36.21	34.85
		1.0	0.0	838.93	-	674.67	564.21	484.83
			1.6P	86.99		84.85	82.81	80.86

Comparison with Previous Work

In the experimental and theoretical work done by Davies *et al.* [2] and Yu *et al.* [8] respectively, a multiplanar joint with in-plane chord member (150×150×6.3mm), in-plane vertical member (90×90×6.3mm) and out-of-plane chord member with dimensions similar to that of the in-plane vertical member was analyzed. The joint is affected by two forces only, namely compression axial force acting through the vertical member and tension axial force acted through the out-of-plane chord member. The ratio between the out-of-plane axial force and the in-plane axial force was taken 0.56. In the research work done before, two boundary conditions are taken for the out-of-plane chord member named free end and restrained end to move vertically.

Comparisons between the results obtained by the proposed model used and experimental and theoretical results obtained are done in order to verify the model used. Table 4 shows the values of elastic stiffness, S, for the experimental work done by Davies *et al.* [2], the theoretical work done by Yu *et al.* [8], and the results of the proposed model developed. From the results tabulated in Table 4 and plotted in Figures 9 and 10, the following conclusions can be investigated:

- Figure 9 shows that there is no significant difference between the values of the elastic stiffness in case of free end or in case of restrained to move vertically only end conditions. While in case of simply supported end condition, the values of the elastic stiffness increase by 18-23% than the values of the free end condition depending on the load condition. From these results, the simply supported end condition seems to be convenient in case of out-of-plane member end conditions.
- Figure 10 shows that there is a clear difference between the values obtained experimentally and theoretically in the research work done before and the values calculated by the proposed model developed. The experimental and theoretical models gave higher elastic stiffness values than the proposed model by 18% and 10% respectively. These

higher values may be due to the presence of the end plates, which are used in the end of both the in-plane vertical member and out-of-plane chord member to distribute the load uniformly. These end plates are modeled with the joint so they may give higher stiffness values.

Table 4 Comparison between the experimental and theoretical results and the proposed model results.

Forces acting on joint	End Conditions at the ends of the out-of-plane member	S (kN/mm)		
		Experimental results by Davies *et al.*[2]	Theoretical results by Yu *et al.* [8]	Proposed model results
P	Free End	126.67	116.00	104.50
	Restrained	140.00	128.00	115.26
	Simply Supported	-	-	123.43
P+ N=0.56P	Free End	114.75	106.00	96.32
	Restrained	136.36	124.67	111.36
	Simply Supported	-	-	118.78

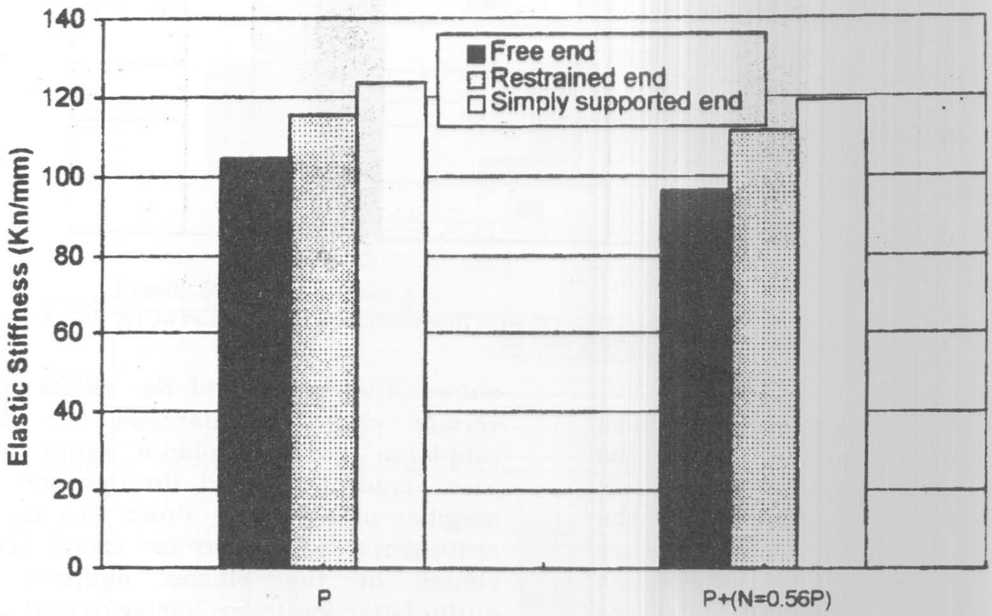

Figure 9 Effect of the out-of-plane end condition on the elastic stiffness of the joint

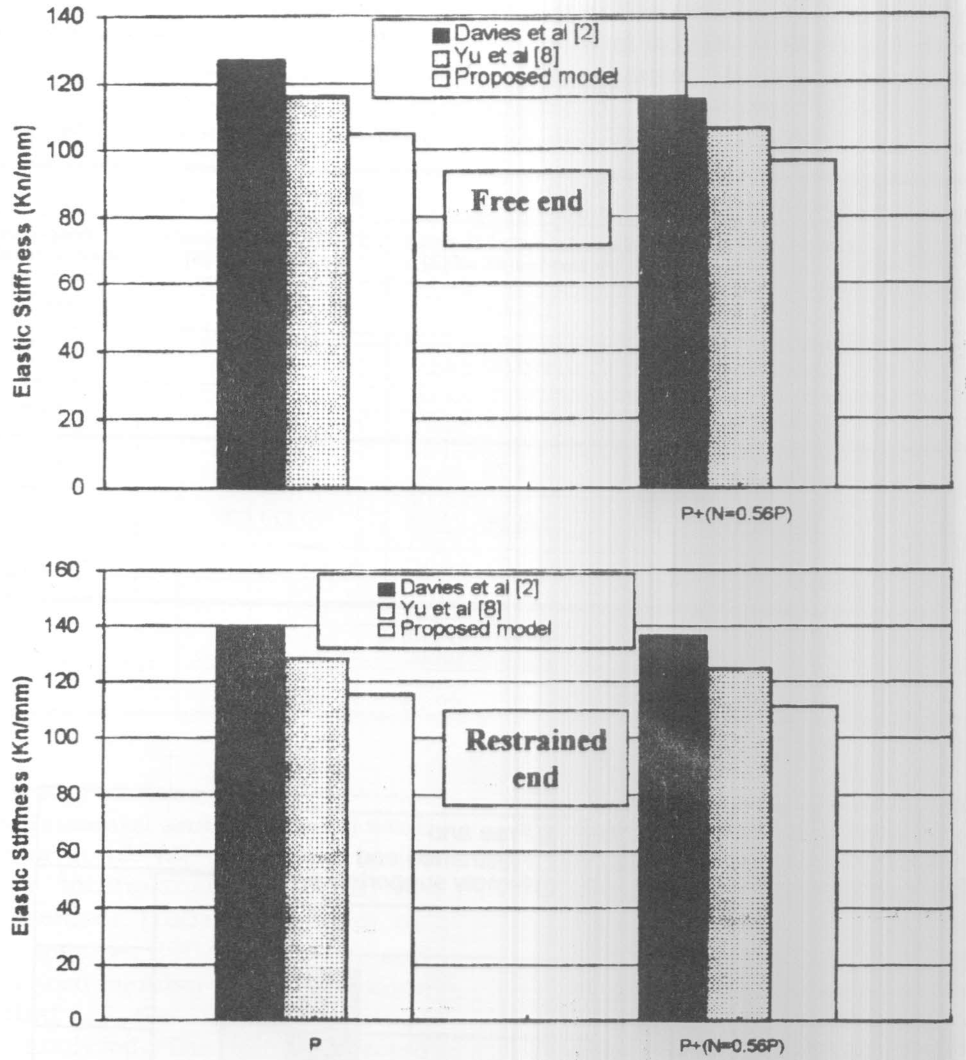

Figure 10 Comparison between the proposed model ress with those obtained by Davies *et al.* [2] and Yu *et al.* [8]

The Multiplanar Effect

Comparison between the elastic stiffness, S, of the multiplanar joints and the uniplanar joints are discussed to evaluate the multiplanar effect. The values of the elastic stiffness of the uniplanar joints are obtained from the research work of Shehata *et al.* [23]. The two types of joints are subjected to an axial force, P, acted through the vertical member of the joint. Table 5 shows the comparison between the results obtained for the two types of joints for different geometrical parameters. Figure 11 shows the values of the elastic stiffness versus chord slenderness, 2γ, for the uniplanar and multiplanar joints under an axial load, P, acted through the vertical member of the joint. From this figure, the multiplanar effect can be clearly seen. The values of the elastic stiffness for all multiplanar joints are higher than that of the uniplanar joints. Table 5 and Figure 11 show that the multiplanar effect increase by increasing the width ratio of the joint, b/B, and chord slenderness, H/t.

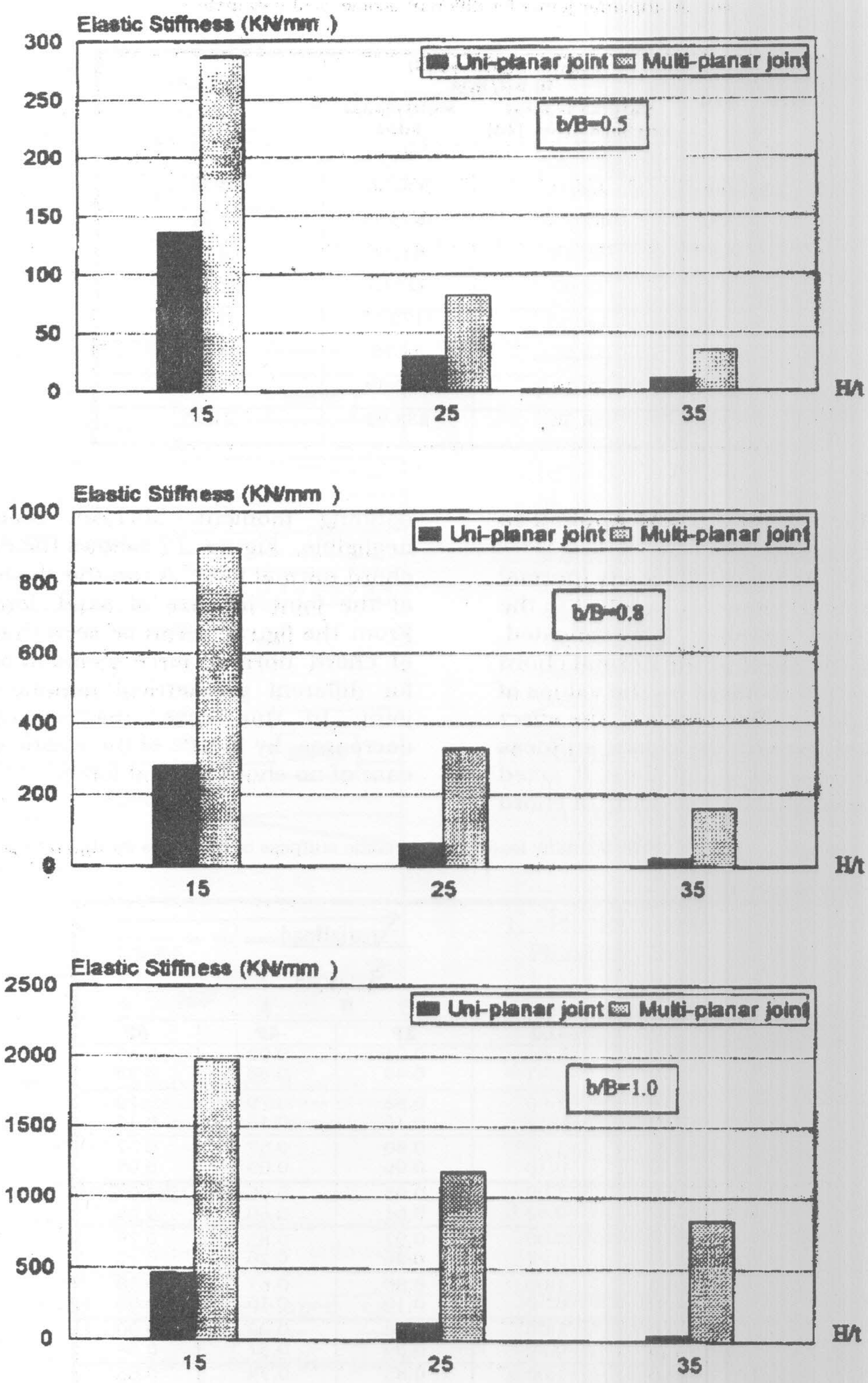

Figure 11 Multiplanar effect of the elastic stiffness for different geometrical parameters

Table 5 Comparison between the values of Elastic Stiffness, S, for both uniplanar and multiplanar joints for different geometrical parameters.

H/t	B/B	Elastic Stiffness (S) in kN/mm		$\frac{S_{m-p}}{S_{u-p}}$
		Uniplanar joint Shehata *et al.* [23]	Multiplanar joint	
15	0.5	135.37	286.94	2.12
	0.8	278.16	896.86	3.22
	1.0	463.61	1975.11	4.26
25	0.5	29.12	81.17	2.78
	0.8	62.00	327.01	
	1.0	120.66	1172.75	9.72
35	0.5	10.56	34.76	3.29
	0.8	22.55	160.49	7.12
	1.0	38.58	838.92	21.75

Influence of the Spatially Loads Applied to the Joint

The effect of the spatially loads (normal force, and bending moment) applied to the out-of-plane chord member is investigated. Table 6 shows the effect of the normal chord force and the chord moment on the values of the elastic stiffness. From table 5, the effect of chord normal force on the elastic stiffness of the joint in case of axial force, P, acted through the vertical member with a chord bending moment, M=1.6P, seems to be negligible. Figure 12 shows the effect of the chord normal force, N, on the elastic stiffness of the joint in case of axial force, P, only. From the figure, it can be seen that the effect of chord normal force seems to be constant for different geometrical parameters of the joint. In this case, the elastic stiffness decreases by 2-10% of the elastic stiffness in case of no chord normal force.

Table 6 Effect of the spatially loads on the elastic stiffness of the joints for different geometrical parameters

H/t	b/B	M	$\frac{S_{spatial load}}{S_{axial load}}$ N			
			0.0	2P	4P	6P
15	0.5	0.0	1.00	0.96	0.92	0.89
		1.6P	0.41	0.40	0.39	0.38
	0.8	0.0	1.00	0.88	0.79	0.72
		1.6P	0.16	0.16	0.15	0.15
	1.0	0.0	1.00	0.80	0.67	0.57
		1.6P	0.10	0.09	0.09	0.09
25	0.5	0.0	1.00	0.98	0.96	0.94
		1.6P	0.62	0.61	0.60	0.59
	0.8	0.0	1.00	0.92	0.85	0.79
		1.6P	0.27	0.26	0.26	0.25
	1.0	0.0	1.00	0.80	0.67	0.58
		1.6P	0.10	0.10	0.10	0.09
35	0.5	0.0	1.00	0.96	0.93	0.90
		1.6P	0.60	0.59	0.57	0.56
	0.8	0.0	1.00	0.85	0.74	0.66
		1.6P	0.25	0.24	0.23	0.22
	1.0	0.0	1.00	0.80	0.67	0.58
		1.6P	0.10	0.10	0.10	0.10

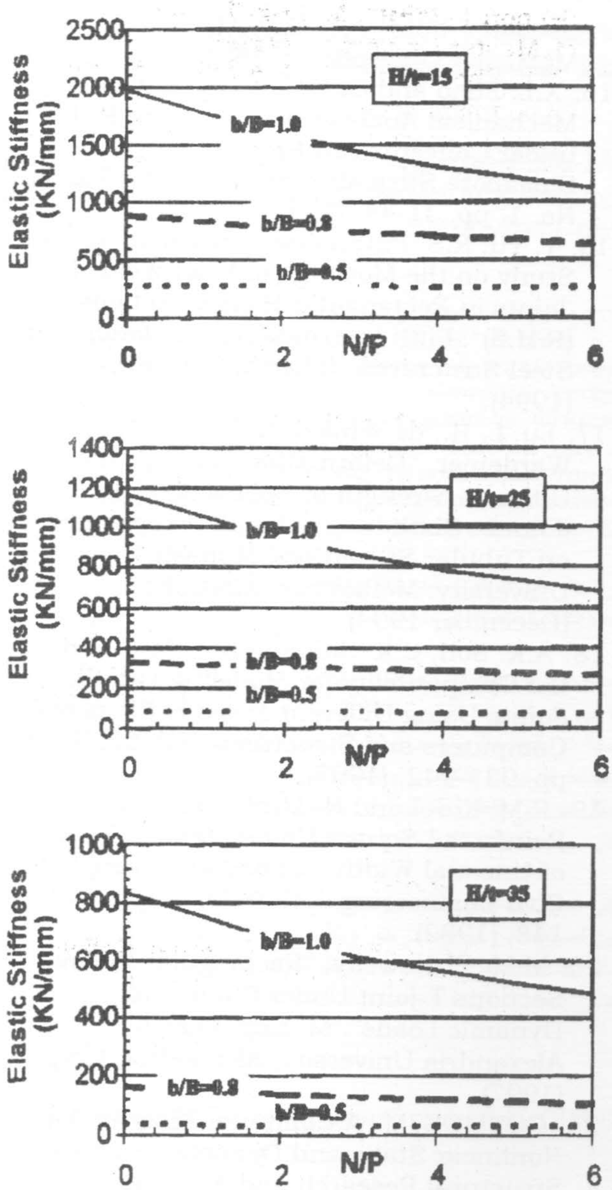

Figure 12 Effect of chord normal force, N, on the elastic stiffness of the joint in case of no bending moment for different geometrical parameters

CONCLUSIONS

Based on the numerical parametric study carried out in this research, the following conclusions may be drawn:

1. The proposed model developed can simulate the multiplanar joint successfully. The results show that there is a quite difference between the proposed model results and the experimental and the theoretical work done before. The reason for that is the moof the end plate of the joint.
2. The simply supported end condition seems to be a convenient solution for the out-of-plane end condition.
3. No significant difference between the values of the elastic stiffness in case of free end
4. The multiplanar effect has a great effect on increasing the elastic stiffness of the joint. It reaches from 2 to 22 times the elastic stiffness of the uniplanar joints depending on the geometrical parameters.
5. The spatially loads acting on the joint decrease the elastic stiffness of the joint by 2-10% of the elastic stiffness in case of no chord normal force and by 40-90% in the presence of chord bending moment. So, the spatially loads must be considered in the analysis of hollow section joints.
6. The influence of the geometrical parameters of the joint must be considered in the analysis of multiplanar joints.
7. Further parametric studies are required in order to quantify the multiplanar effect on the ultimate capacity of the joints in hollow sections.

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