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Stevin Report 6.94.20/023.02

PARAMETER STUDIES FOR CONNECTIONS BETWEEN I-BEAMS AND RHS COLUMNS

Technical Report No. 5

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Research Location: Delft University of Technology,
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Summary

The objective of this Ph.D. research work is to investigate the static behaviour of connections between plates or I-beams and rectangular hollow section columns and to establish design formulae for these connections. The influence of multiplanar loading effects and the composite action (steel-concrete columns and floors) on the stiffness and strength are part of this investigation.

With this aim, experimental research is carried out in the framework of ECSC project 7210-SA/611 at Delft University of Technology and TNO Building and Construction Research. The numerical research is carried out at Delft University of Technology in the framework of the "Commission BEEK" programme.

The calibrations of the numerical modelling with the experimental work is finished except for connections with composite floors. The effect of the composite action and the effect of the multiplanar loading on the behaviour of I-beam to concrete filled RHS column connections with β = 0.4, 0.6 has been investigated and have been presented in the previous reports No.1 to No.3 (Lu et al, 1992, 1993a, 1993b).

The parameter studies for welded connections between plates and RHS columns loaded by compression and connections between I-beams and RHS column loaded by compression or in-plane bending moment are completed. The results of the parameter studies are presented in this report. Comparisons between plate to RHS column connections and I-beam to RHS column connections have been done, so that the interaction of the flanges on the connection behaviour is clear. Each multiplanar connection has been investigated for five load ratios to determine the multiplanar load effect.

Based on the numerical results and analytical models, strength formulae for plate to RHS column connection loaded by compression and I-beam to RHS column connection loaded by compression or in-plane bending moment have been developed.

1 Introduction

Welded multiplanar connections between I-beams and rectangular hollow section (RHS) columns are attractive for use in offshore deck structures and industrial buildings, while bolted multiplanar connections between I-beams and rectangular hollow section columns offer economical possibilities for industrial buildings, especially if the composite action of the floors is taken into account. By filling the columns with concrete sufficient fire resistance can be achieved and the strength and stiffness of the connections can be increased. The strength and stiffness of the connections can also be increased by using a steel or a composite steel-concrete floor.

To determine the static behaviour of these connections with or without the influence of the concrete infill in RHS columns and the influence of a steel or a concrete-steel floor, experimental and numerical investigations have been carried out. The experimental research has been carried out in the framework of ECSC project 7210-SA/611 at Delft University of Technology and TNO Building and Construction Research. The numerical research is carried out at Delft University of Technology in the framework of the "Commission BEEK" programme for a Ph.D project.

The experimental results have been used for the calibrations of the numerical models. Good agreement has been found between numerical and experimental results. (see report No.1 to No.3 of Lu, et al.). Therefore, further parametric studies have been carried out using finite element analyses.

From the previous experimental and numerical research, it has been shown that the static behaviour of the connections between plates or I-section beams and RHS columns depends on the geometrical parameters of the connections, such as β (width ratio between I-beam flange and RHS column b_1/b_0), 2γ (width to thickness ratio of RHS column b_0/t_0), η (I-beam depth to RHS column width ratio $h1/b_0$) etc. In order to determine the individual influence of the most important geometrical parameters as mentioned above, numerical parametric research has been carried out initially for welded uniplanar and multiplanar connections without a concrete infill in the columns and without a composite floor. For multiplanar connections, the strength and stiffness of the connection can be significantly influenced by the load ratios applied on the two sets of the plates or I-beams (multiplanar load effect), thus five load ratios have been considered for each multiplanar connection to investigate the multiplanar load effect.

The results of the parameter study for the welded plate to RHS column connections loaded by compression will be presented at the 5th International Offshore and Polar Engineering (Lu, et al, June 6-11, 1995, The Hague), see Appendix 1. The results for I-beam to RHS column connections loaded by compression on beams will be presented at the 14th International Conference on Offshore Mechanics and Arctic Engineering (Lu, June 18 - 22, 1995, Copenhagen), see Appensix 2. The results of the parameter studies for I-beam to RHS column connections loaded by in-plane bending are presented in this report.

Based on the numerical results obtained so far, strength formulae for plate to RHS column connection loaded by compression and I-beam to RHS column connection loaded by compression or in-plane bending moment have been derived.

2 Parameter research programme

The parameter research programme is shown in table 1 to table 4. The main geometrical parameters β, 2γ, τ, η which determine the behaviour of the connection are shown in figure 1. Six β values (β = 0.18, 0.3, 0.5, 0.73, 0.87, 0.93), three 2γ values (2γ = 15.79, 25.0, 37.5) and five η (η = 0.3, 0.6, 0.9, 1.0, 2.0) have been selected. The influence of the multiplanar load effect has been investigated by analysing each multiplanar connection with five different load ratios applied on the two sets of braces. These load ratios are J = 0, +0.5, +1, -0.5 and -1.

The steel used for the RHS column in the numerical modelling is Fe510 with a yield stress of 355 N/mm^2 and an ultimate stress of 510 N/mm^2. In order to avoid plate or beam failure before connection failure, a steel grade of StE 690 with a nominal yield strength of 690 N/mm^2 and an ultimate strength of 1200 N/mm^2 is used for all plates and I-beams.

Pre- and post processing have been performed by using program IDEAS. The finite element analyses have been carried out with program MARC. Eight noded thick shell elements (MARC element type 22) have been used for modelling of the steel members of the connections, which is in accordance with the calibrations with the experiments.

It should be mentioned that throughout the parameter study, butt welds are considered which are stronger than the parent material being connected. Since the nominal size of the fillet part of butt welds according to AWS (1992) and Eurocode 3 (1992) is relative small, no weld elements have been modelled in the numerical models. However, the actual weld sizes are general larger than the nominal weld sizes, which may lead to an increase of the actual connection strength.

During the numerical analyses, displacement - control has been used for J = 0 and 1. For J = -1, -0.5 and +0.5, load - control is used so that a fixed load ratio applied on the connections can be maintained even after plastic deformation.

3 Results of parameter study

Since no peak loads have been obtained from the numerical analyses, the connection strength is taken at a deformation limit of $3\%b_0$ at the intersection of the compression flange and the chord face in accordance with Lu (1994b).

3.1 Plate to RHS column connection

The results of the FE analyses for uniplanar and multiplanar plate to RHS column connections as shown in table 1 will be presented in the paper "Parametric study on the static strength of uniplanar and multiplanar plate to RHS column connections" for the 5th International Offshore and Polar Engineering in The Hague (Lu, et al, 1995). The load - displacement curves are shown in figures 3 to 19 of appendix 1. The connection strength at a deformation limit of $3\%b_0$ is shown in table 5.

3.2 I-beam to RHS column connection loaded by compression

The results of the FE analyses for uniplanar and multiplanar I-beam to RHS column connections loaded by compression on the beams will be presented in the paper "The static strength of uniplanar and multiplanar I-beam to RHS column connections loaded by axial compression" at the 14th International Conference on Offshore Mechanics and Arctic Engineering (Lu, June 18 - 22, 1995, Copenhagen, see appendix 2). The load - displacement curves are shown in figures 2 to 17. The connection strengths at a deformation limit of $3\%b_0$ are shown in table 6 and 7.

3.3 I-beam to RHS column connection loaded by in-plane bending moment

The moment - rotation curves for uniplanar connections loaded by in-plane bending have been given in the previous report No.4 (Lu et al, 1994a, see figure 6 to figure 9). The moment - rotation curves multiplanar connections loaded by in-plane bending xxb1 to xxb9 and xxb14 to xxb15 are shown in figures 18 to 28. The numerically determined strengths at the deformation limit of $3\%b_0$ are summarized in table 8 for uniplanar and multiplanar connections.

To get the relation between I-beam to RHS column connections loaded by bending moments and axially loaded plate to RHS column connections, the connection strength for bending $M_{u,xb}$ has been compared with the connection strength $N_{u,xp}$. On the vertical axis of figure 29, the non-dimensional strength ratio $M_{u,xb} / (h_m N_{u,xp})$is given. Figure 29 shows that for $\eta > 0.6$, the non-dimensional strength ratio $M_{u,xb} / (h_m N_{u,xp})$ is about 1.0. For $\eta \leq 0.6$, $M_{u,xb} / (h_m N_{u,xp})$ can reach 1.3. However, for theses connections, the rotations of the connections are very large. The serviceability criterion become critical. Therefore, the strength of I-beam to RHS column connection $M_{u,xb}$ can be obtained by multiplying the strength $N_{u,xp}$ for plate to RHS column connection by h_m :

$$M_{u,xb} = N_{u,xp} * h_m \tag{1}$$

This is in accordance with the CIDECT design guide (1992).

Further, the non-dimensional strength of the multiplanar connections with J = 0 has been compared with the strength of the corresponding uniplanar connections. As shown in figure 30, almost no difference is found between the strength of the multiplanar connections with J = 0 and the strength of the corresponding uniplanar connections. Therefore, the same strength formula as used for uniplanar connection can be used for multiplanar connection with J = 0.

Finally, the multiplanar load effect is shown in figure 31. On the vertical axis, the strength ratio between connections with $J \neq 0$ and connections with $J=0$ is given. It can be seen that when a connection is loaded with a positive load ratio, the connection strength increases. The increase of the connection strength for a positive load ratio is more pronounced for connections with a small 2γ value and a higher β value. In this case, the load transfer is more directly by axial stresses in the corners. For other cases however, the increase of the connection strength is less than 20%. For the time being, it is proposed to use the same strength formula as used for uniplanar connection as a conservative lower bound for multiplanar connection with J > 0. However, further analysis is required.

For negative load ratios however, the connection strength decreases significantly, linear with J. This multiplanar loading influence is described by equation (2) :

$$f(J) = 1 + J\,(0.95\beta - 0.6\beta^2) \qquad J < 0 \tag{2}$$

The strength of multiplanar I-beam to RHS column connection $M_{u,xxb}$ with $J < 0$ is obtained by multiplying $M_{u,xb}$ by function f(J):

$$M_{u,xxb} = f(J)\, M_{u,xb} \tag{3}$$

The strength formulea for butt welded connections between plates or I-beams and RHS columns loaded by compression or in-plane bending moment are summarized in table 9.

4 Work to be done

Period 6 : November 1994 - May 1995

- numerical simulation of concrete floor
- completion of literature studies
- further analyses of the experimental and numerical results
- recommendations for design formulae

5 List of symbols

b_0 : width of RHS column
b_1 : width of the flange of an I-beam
h_1 : height of an I-beam
h_m : $h_m = h_1 - t_1$
t_0 : wall thickness of RHS column
t_1 : thickness of the flange of an I-beam
f_{y0} : yield stress of RHS member
f_{y1} : yield stress of I-beams
f(J) : multiplanar load effect function
$f(\beta,\eta)$: effect of the second flange and web of an I-beam
J : load ratio on multiplanar connections $J = N_2/N_1$
$M_{u,xb}$: connection strength at a deformation limit of 3%b_0 at the flange connection for uniplanar I-beam to RHS column connections loaded by in-plane bending
$M_{u,xxb}$: connection strength at a deformation limit of 3%b_0 at the flange connection for multiplanar I-beam to RHS column connections loaded by in-plane bending
N_i : axial compression load applied to the I-beams, i =1, 2
$N_{u,xb}$: connection strength at a deformation limit of 3%b_0 at the flange connection for uniplanar I-beam to RHS column connections loaded by compression
$N_{u,xxb}$: connection strength at a deformation limit of 3%b_0 at the flange connection for multiplanar I-beam to RHS column connections loaded by compression

$N_{u,xp}$: connection strength at a deformation limit of $3\%b_0$ at the plate connection for uniplanar plate to RHS column connections loaded by compression

$N_{u,xxp}$: connection strength at a deformation limit of $3\%b_0$ at the plate connection for multiplanar plate to RHS column connections loaded by compression

β : width ratio between I-beam's flange and RHS column b_1/b_0

2γ : width to thickness ratio of RHS column b_0/t_0

η : I-beam depth to RHS column width ratio $h1/b_0$

τ : thickness ratio of I-beam's flange and RHS column t_1/t_0

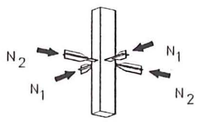
Δ : local deformation at RHS column face

RHS : rectangular hollow section

6 References

1. American Welding Society, Structural Welding Code, AWS D1.1-88, 1992
2. Eurocode 3, Design of Steel Structures (1992). Part 1: "General Rules and Rules for Buildings".
3. Lu, L.H., Puthli, R.S, Wardenier, J. (1992) , "The Static Strength of Multiplanar Connections between I-beams and Rectangular Hollow Section Columns", Stevin Report 6.92.24/A1/11.10, Delft.(Beek report No.1).
4. Lu, L.H., Puthli, R.S, Wardenier, J. (1993a), "The Static Strength of Multiplanar Connections between I-beams and Rectangular Hollow Section Columns", Stevin Report 6.93.17/A1/11.10, Delft.(Beek report No.2).
5. Lu, L.H., Puthli, R.S, Wardenier, J. (1993b), "The Static Strength of Multiplanar Connections between I-beams and Rectangular Hollow Section Columns", Stevin Report 6.93.39/11.10, Delft. (Beek report No.3).
6. Lu, L.H., Wardenier, J. (1994), "Parameter Studies for Connections between I-beams and Rectangular Hollow Section Columns", Stevin Report 6.94.15/023.02, Delft.(Beek report No.4).
7. Lu, L.H., Winkel, G.D. de, Yu, Y., Wardenier, J. (1994b), "Deformation Limit for the Ultimate Strength of Hollow Section Joints", Proc. The Sixth International Symposium on Tubular Structures, Melbourne, Australia.
9. Lu, L.H., Wardenier, J. (1995a), "Parametric Study on the Static Strength of Uniplanar and Multiplanar Plate to RHS column Connections", to be presented at the 5th International Offshore and Polar Engineering Conference, June 6 - 11, 1995, The Hage, The Netherlands.
10. Lu, L.H., Wardenier, J. (1995b), "The Static Strength of Uniplanar and Multiplanar I-beam to RHS column Connections Loaded by Axial Compression", to be presented at the 14th International Conference on Offshore Mechanics and Arctic Engineering, June 18 - 22, 1995, Copenhagen.
11. Packer, J.A., Wardenier, J., Kurobane, Y., Dutta, D., Yeomans, N. (1992). "Design Guide for Rectangular Hollow Section (RHS) Joints under Predominantly Static Loading" ,Published by Verlag TÜV Rheinland GmbH, Köln.

Table 1 Summary of parameter studies for plate to RHS column connections loaded by compression

		Nominal dimensions (mm)				Non-dimensional parameters		
		b_0	t_0	b_1	t_1	β	2γ	τ
xp1	xxp1	300	19.0	91	8.0	0.3	15.8	0.42
xp2	xxp2	300	12.0	91	8.0	0.3	25.0	0.67
xp3	xxp3	300	8.0	91	8.0	0.3	37.5	1.00
xp4	xxp4	300	19.0	150	10.7	0.5	15.8	0.49
xp5	xxp5	300	12.0	150	10.7	0.5	25.0	0.89
xp6	xxp6	300	8.0	150	10.7	0.5	37.5	1.34
xp7	xxp7	300	19.0	220	19.0	0.73	15.8	1.00
xp8	xxp8	300	12.0	220	19.0	0.73	25.0	1.58
xp9	xxp9	300	8.0	220	19.0	0.73	37.5	2.37
xp10	--	300	19.0	280	13.0	0.93	15.8	0.68
xp11	--	300	12.0	280	13.0	0.93	25.0	1.08
xp12	--	300	8.0	280	13.0	0.93	37.5	1.62
xp13	xxp13	300	19.0	55	5.7	0.18	15.8	0.30
xp14	xxp14	300	12.0	55	5.7	0.18	25.0	0.48
xp15	xxp15	300	8.0	55	5.7	0.18	37.5	0.71
xp16	--	300	19.0	260	12.5	0.87	15.8	0.66
xp17	--	300	12.0	260	12.5	0.87	25.0	1.04
xp18	--	300	8.0	260	12.5	0.87	37.5	1.56

Note : xp - uniplanar connection
xxp - multiplanar connection

Table 2 Summary of parameter study I-beams to RHS column connections loaded by compression

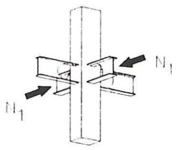
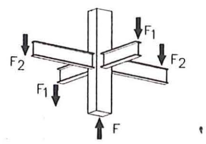
		Nominal dimensions (mm)					Non-dimensional parameters			
		b_0	t_0	b_1	t_1	h_1	β	2γ	τ	η
xb1a	xxb1a	300	19.0	91	8.0	180	0.3	15.8	0.42	0.6
xb2a	xxb2a	300	12.0	91	8.0	180	0.3	25.0	0.67	0.6
xb3a	xxb3a	300	8.0	91	8.0	180	0.3	37.5	1.00	0.6
xb4a	xxb4a	300	19.0	150	10.7	300	0.5	15.8	0.56	1.0
xb5a	xxb5a	300	12.0	150	10.7	300	0.5	25.0	0.89	1.0
xb6a	xxb6a	300	8.0	150	10.7	300	0.5	37.5	1.34	1.0
xb7a	xxb7a	300	19.0	220	19.0	600	0.73	15.8	1.00	2.0
xb8a	xxb8a	300	12.0	220	19.0	600	0.73	25.0	1.58	2.0
xb9a	xxb9a	300	8.0	220	19.0	600	0.73	37.5	2.37	2.0
xb10a	--	300	19.0	280	13.0	270	0.93	15.8	0.68	0.9
xb11a	--	300	12.0	280	13.0	270	0.93	25.0	1.08	0.9
xb12a	--	300	8.0	280	13.0	270	0.93	37.5	1.62	0.9
xb14a	xxb14a	300	12.0	55	5.7	100	0.18	25.0	0.48	0.3
xb15a	xxb15a	300	8.0	55	5.7	100	0.18	37.5	0.71	0.3

Table 3 The influence of η for axially loaded uniplanar I-beams to RHS column connections (XBAX-E)

	η=0.3	η=0.6	η=1.0	η=1.5	η=2.0	η=2.5
β=0.18	xb14a	xb14a-e2	xb14a-e3	xb14a-e4	xb14a-e5	
β=0.5	xb5a-e1	xb5a-e2	xb5a	xb5a-e4	xb5a-e5	xb5a-e6
β=0.73	xb8a-e1	xb8a-e2	xb8a-e3		xb8a	xb8a-e6
β=0.93	xb11a-e1	xb11a-e2		xb11a-e4	xb11a-e5	xb11a-e6

Table 4 Summary of parameter studies for I-beams to RHS column connections loaded by an in-plane bending moment

		Nominal dimensions (mm)					Non-dimensional parameters			
		b_0	t_0	b_1	t_1	h_1	β	2γ	τ	η
xb1	xxb1	300	19.0	91	8.0	180	0.3	15.8	0.42	0.6
xb2	xxb2	300	12.0	91	8.0	180	0.3	25.0	0.67	0.6
xb3	xxb3	300	8.0	91	8.0	180	0.3	37.5	1.00	0.6
xb4	xxb4	300	19.0	150	10.7	300	0.5	15.8	0.49	1.0
xb5	xxb5	300	12.0	150	10.7	300	0.5	25.0	0.89	1.0
xb6	xxb6	300	8.0	150	10.7	300	0.5	37.5	1.34	1.0
xb7	xxb7	300	19.0	220	19.0	600	0.73	15.8	1.00	2.0
xb8	xxb8	300	12.0	220	19.0	600	0.73	25.0	1.58	2.0
xb9	xxb9	300	8.0	220	19.0	600	0.73	37.5	2.37	2.0
xb10	--	300	19.0	280	13.0	270	0.93	15.8	0.68	0.9
xb11	--	300	12.0	280	13.0	270	0.93	25.0	1.08	0.9
xb12	--	300	8.0	280	13.0	270	0.93	37.5	1.62	0.9
xb14	xxb14	300	12.0	55	5.7	100	0.18	25.0	0.48	0.3
xb15	xxb15	300	8.0	55	5.7	100	0.18	37.5	0.71	0.3
xb18	--	300	8.0	260	12.5	250	0.87	37.5	1.56	0.8
xb20	--	300	12.0	220	11.0	210	0.73	25.0	1.38	0.7

Note : xb - uniplanar connection
xxb - multiplanar connection

Table 5 The numerically determined strength at a deformation limit of 3%b_0 for uniplanar and multiplanar plate to RHS column connections loaded by axial compression

$N_{u,xp}$ / f_{y0} t_0^2		$N_{u,xxp}$ / f_{y0} t_0^2					
			J = 0	J = +0.5	J = +1	J = -0.5	J = -1
xp13	3.0634	xxp13	3.0614	3.1621	3.3955	2.6257	2.1794
xp14	2.8288	xxp14	2.8307	2.9922	3.1087	2.5070	2.0907
xp15	2.8397	xxp15	2.8454	3.1483	3.2496	2.4733	2.1093
xp1	3.4184	xxp1	3.4196	3.5547	3.7885	2.9458	2.4269
xp2	3.3761	xxp2	3.3727	3.5490	3.6718	2.9297	2.4063
xp3	3.4260	xxp3	3.4546	3.7549	3.8164	2.9341	2.4565
xp4	4.5465	xxp4	4.5435	4.8645	5.2840	3.8099	3.1034
xp5	4.4080	xxp5	4.4280	4.6613	4.7922	3.7289	3.0742
xp6	4.5267	xxp6	4.5876	4.9178	4.8753	3.7866	3.1084
xp7	7.1503	xxp7	7.2352	8.2542	9.3794	5.8342	4.7906
xp8	6.7893	xxp8	6.7994	7.4553	7.6285	5.5170	4.4509
xp9	7.0482	xxp9	7.1336	7.7413	7.0044	5.7085	4.6134
xp10	10.5821						
xp11	11.4453						
xp12	11.8922						
xp16	8.9698						
xp17	8.8057						
xp18	9.3947						

Table 6 The numerically determined strength at a deformation limit of 3%b_0 for uniplanar I-beam to RHS column connections loaded by compression

Connections	β	2γ	η	τ	$N_{u,xb} / f_{y0}\, t_0^2$
xb14a	0.18	25.0	0.3	0.48	3.8023
xb14a-e2	0.18	25.0	0.6	0.48	4.4399
xb14a-e3	0.18	25.0	1.0	0.48	5.3565
xb14a-e4	0.18	25.0	1.5	0.48	6.5100
xb14a-e5	0.18	25.0	2.0	0.48	6.5100
xb5a-e1	0.50	25.0	0.3	0.89	5.9543
xb5a-e2	0.50	25.0	0.6	0.89	7.0073
xb5a	0.50	25.0	1.0	0.89	8.1301
xb5a-e4	0.50	25.0	1.5	0.89	9.3983
xb5a-e4-w	0.50	25.0	1.5	0.89	8.8488
xb5a-e5	0.50	25.0	2.0	0.89	10.5134
xb5a-e5-w	0.50	25.0	2.0	0.89	8.8674
xb5a-e6	0.50	25.0	2.5	0.89	11.7185
xb8a-e1	0.73	25.0	0.3	1.58	9.6066
xb8a-e2	0.73	25.0	0.6	1.58	11.3306
xb8a-e3	0.73	25.0	1.0	1.58	12.8527
xb8a	0.73	25.0	2.0	1.58	15.1526
xb8a-e6	0.73	25.0	2.5	1.58	16.3014
xb11a	0.93	25.0	0.9	1.08	22.0037
xb11a-e1	0.93	25.0	0.3	1.08	18.1600
xb11a-e2	0.93	25.0	0.6	1.08	20.5453
xb11a	0.93	25.0	0.9	1.08	22.0037
xb11a-e4	0.93	25.0	1.5	1.08	23.6686
xb11a-e5	0.93	25.0	2.0	1.08	25.0641
xb11a-e6	0.93	25.0	2.5	1.08	26.4737
xb15a	0.18	37.5	0.3	0.71	3.7421
xb1a	0.30	15.8	0.6	0.42	5.3766
xb2a	0.30	25.0	0.6	0.66	5.2168
xb3a	0.30	37.5	0.6	1.00	5.0821
xb4a	0.50	15.8	1.0	0.56	8.3753
xb6a	0.50	37.5	1.0	1.33	8.0048
xb7a	0.73	15.8	2.0	1.00	15.9237
xb9a	0.73	37.5	2.0	2.37	15.1091
xb10a	0.93	15.8	0.9	0.68	19.3814
xb12a	0.93	37.5	0.9	1.62	23.4569

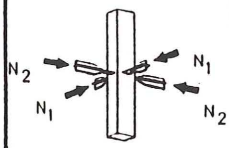
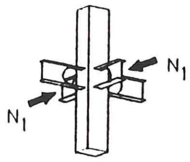
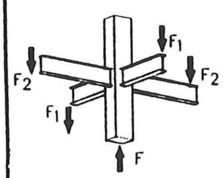
Table 7 The numerically determined strength at a deformation limit of $3\%b_0$ for multiplanar I-beam to RHS column connections loaded by compression

	$N_{u,xxb} / f_{y0} t_0^2$				
name	J = 0	J = +0.5	J = +1	J = -0.5	J = -1
xxb14a	3.8108	4.0338	4.1678	2.5880	3.2003
xxb15a	3.7680	4.1575	4.2165	2.5716	3.1299
xxb1a	5.4014	5.7928	6.3607	3.4347	4.2918
xxb2a	5.2479	5.5197	5.7308	3.3585	4.2383
xxb3a	5.1770	5.6201	5.7198	3.3190	4.1305
xxb4a	8.4654	9.4871	10.7285	5.3022	6.6612
xxb5a	8.2211	8.6970	9.0965	5.2165	6.5662
xxb6a	8.2166	8.8079	8.9723	5.2357	6.5150
xxb7a	16.3870	19.3100	22.6163	10.3290	12.9834
xxb8a	15.3106	16.8441	17.7192	9.6938	12.1409
xxb9a	15.3685	16.9359	16.1810	9.9021	12.3217

Table 8 The numerically determined strength at a deformation limit of $3\%b_0$ for multiplanar I-beam to RHS column connections loaded by in-plane bending moment

$M_{u,xb}/(f_{y0} * t_0^2 * h_m)$		$M_{u,xxb}/(f_{y0} * t_0^2 * h_m)$					
			J = 0	J = +0.5	J = +1	J = -0.5	J = -1
xb14	3.3594	xxb14	3.3595	3.4231	3.4191	3.2374	2.9445
xb15	3.8619	xxb15	3.8639	3.9049	3.9783	3.6509	3.3247
xb1	3.6008	xxb1	3.6035	3.6602	3.7432	3.2836	2.7718
xb2	3.8678	xxb2	3.8781	3.9476	3.8521	3.4761	2.9531
xb3	4.4389	xxb3	4.4548	4.5921	4.2608	3.8876	3.3146
xb4	4.3282	xxb4	4.7216	5.0065	5.3050	3.8974	3.1482
xb5	4.6105	xxb5	4.6365	4.8265	4.7992	3.8572	3.1325
xb6	4.8650	xxb6	4.9359	5.2052	4.8935	4.0562	3.3264
xb7	7.5599	xxb7	7.8464	8.9852	10.1052	6.0878	4.8572
xb8	7.1172	xxb8	7.2165	8.1874	8.2942	5.8356	4.6746
xb9	7.2369	xxb9	7.3855	8.1097	7.4748	5.8527	4.6932
xb10	10.5789						
xb11	11.6661						
xb12	12.4204						
xb18	9.4932						
xb20	7.0520						

Table 9 Strength formulea for plate to RHS column connections and I-beam to RHS column connections

	Uniplanar connection	Multiplanar connection
	Chord face yielding : $\frac{N_{u,xp}}{f_{y0}t_0^2} = (0.5 + 0.7\beta) * \frac{4}{\sqrt{1-0.9\beta}}$ Chord side wall failure : $N_{u,xp} = 2(t_1 + 5t_0) f_{y0}t_0$	$N_{u,xxb} = f(J) N_{u,xb}$ $f(J) = 1 + 0.2J - 0.2\beta J^2$
	Chord face yielding : $N_{u,xb} = f(\beta,\eta) N_{u,xp}$ For $\eta < 0.5$: $f(\beta, \eta) = 1 + \frac{\eta}{0.5} \{ f(\beta, \eta=0.5) - 1 \}$ For $\eta \geq 0.5$: $f(\beta, \eta) = \{\frac{1.25}{1-0.9\beta} + \frac{\eta}{(0.8+2.4\beta)\sqrt{1-0.9\beta}}\}\{1-(0.9\beta)^2\}^*$ Chord side wall failure : $N_{u,xb} = 4 (t_1+5t_0) f_{y0}t_0$ for $h_1 \geq 2t_1+5t_0$ $N_{u,xb} = 2 (h_1+5t_0) f_{y0}t_0$ for $h_1 < 2t_1+5t_0$	$N_{u,xxb} = f(J) N_{u,xb}$ $f(J) = 1$ $J \geq 0$ $f(J) = 1 + 0.37J$ $J < 0$
	$M_{u,xb} = N_{u,xp} * h_m$	$M_{u,xxb} = f(J) M_{u,xb}$ $f(J) = 1$ $J \geq 0$ $f(J) = 1+J(0.95\beta-0.6\beta^2)$ $J < 0$

* This needs further analysis (simplicication)

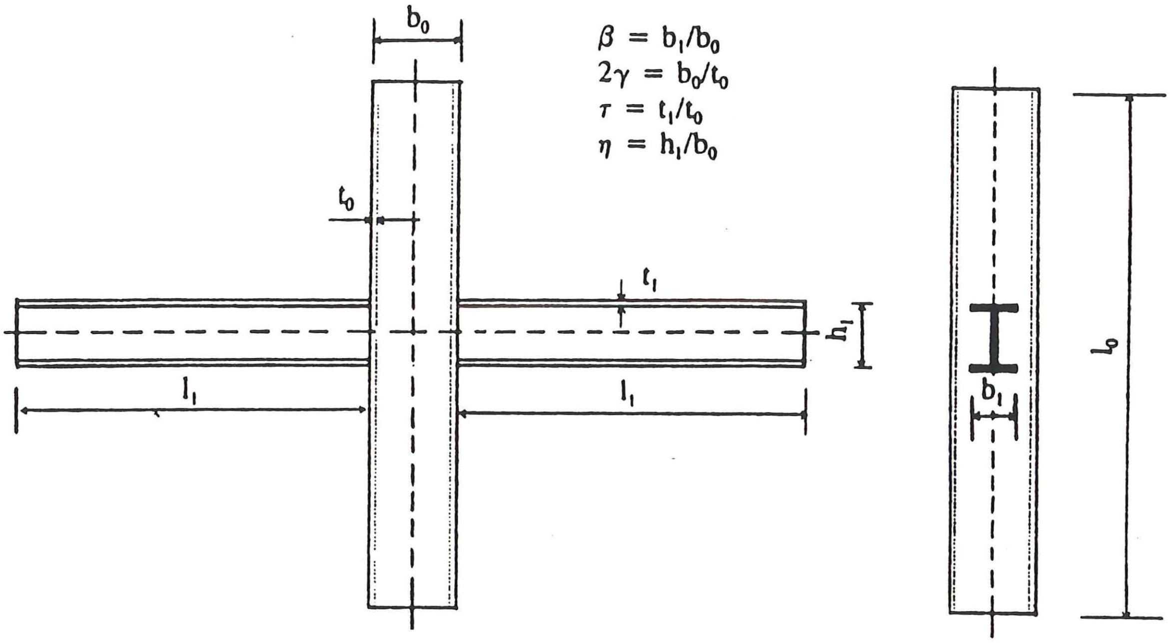


Fig. 1 Configuration of plate or I-beam to RHS column connection

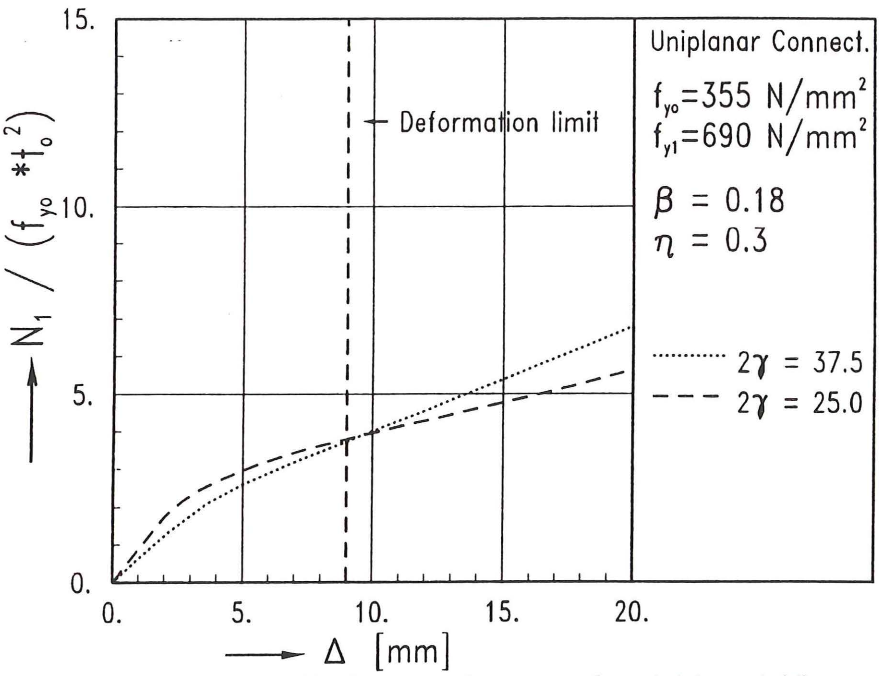


Fig. 2 Load - displacement curves for xb14a-xb15a

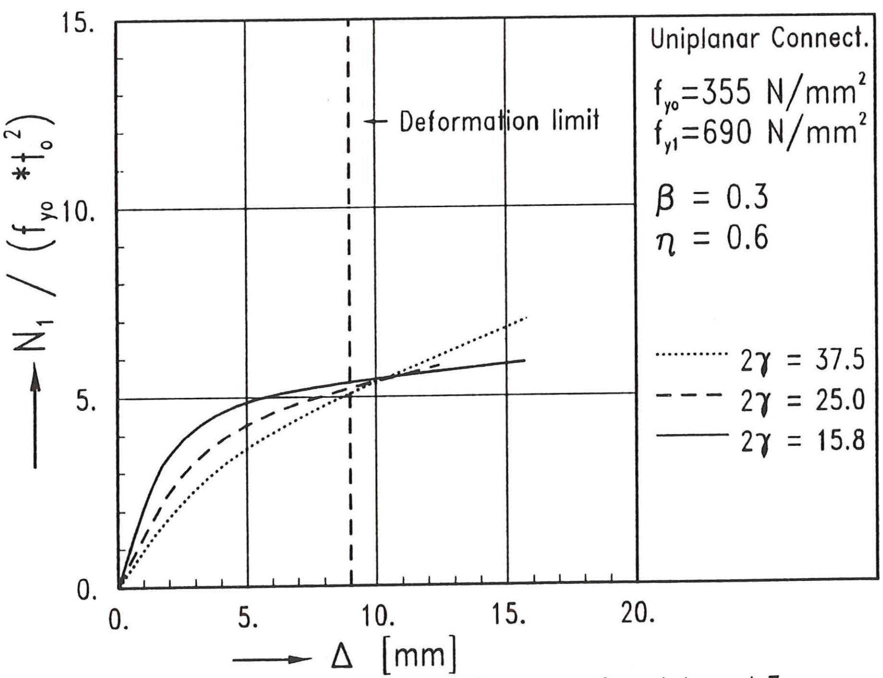


Fig. 3 Load - displacement curves for xb1a-xb3a

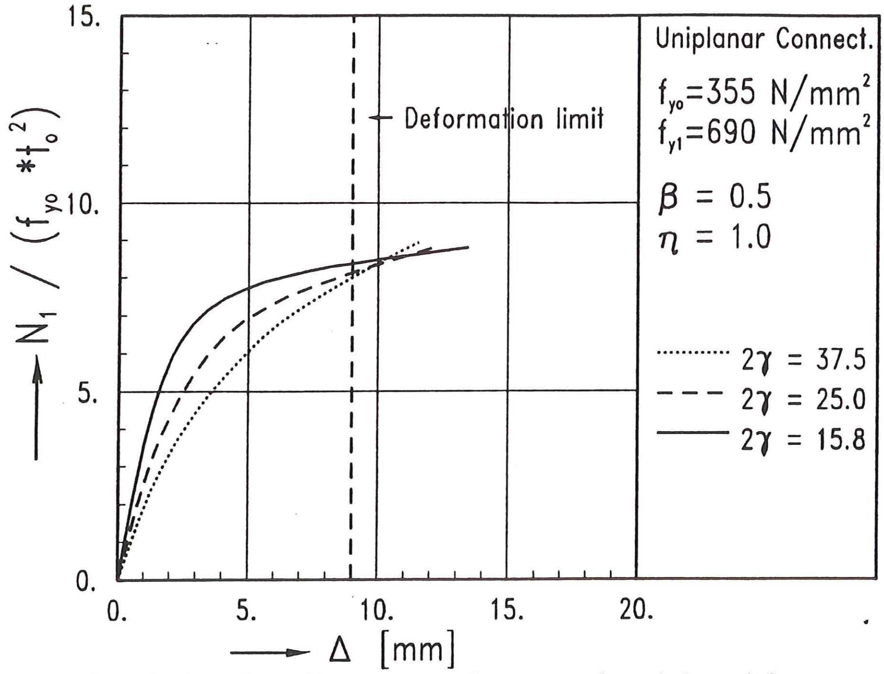


Fig. 4 Load - displacement curves for xb4a-xb6a

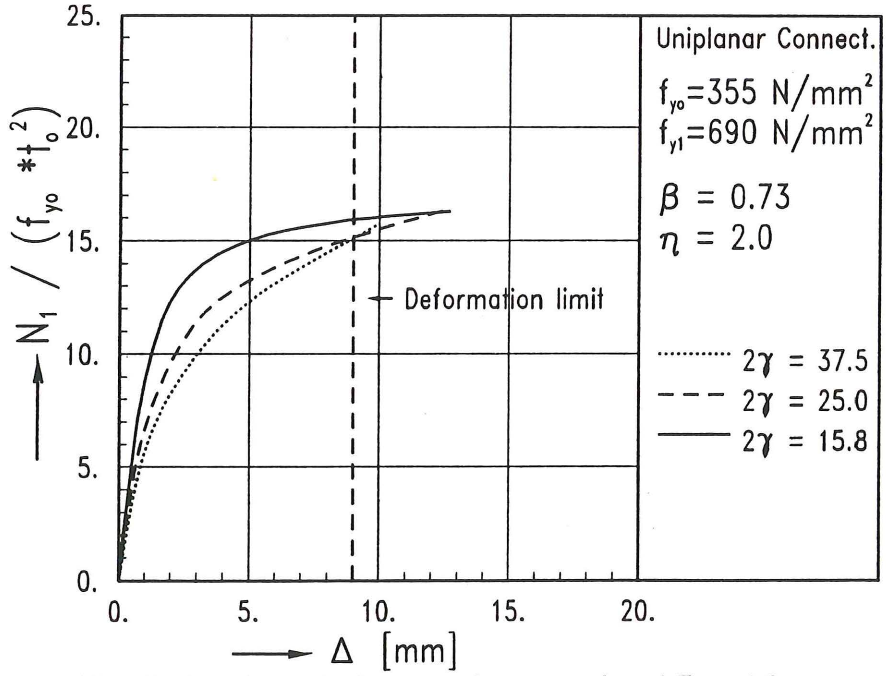


Fig. 5 Load - displacement curves for xb7a-xb9a

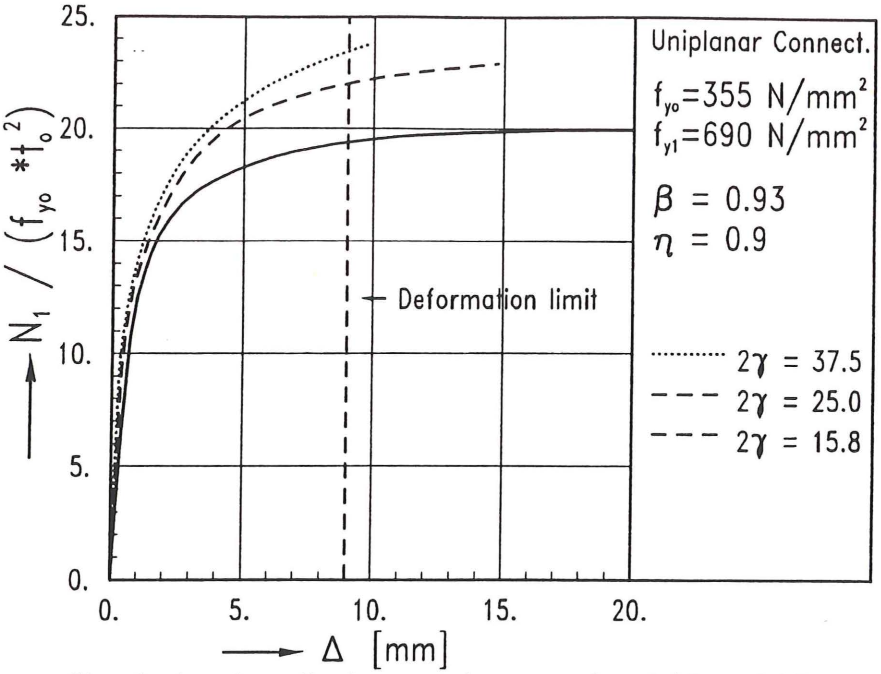


Fig. 6 Load – displacement curves for xb10a–xb12a

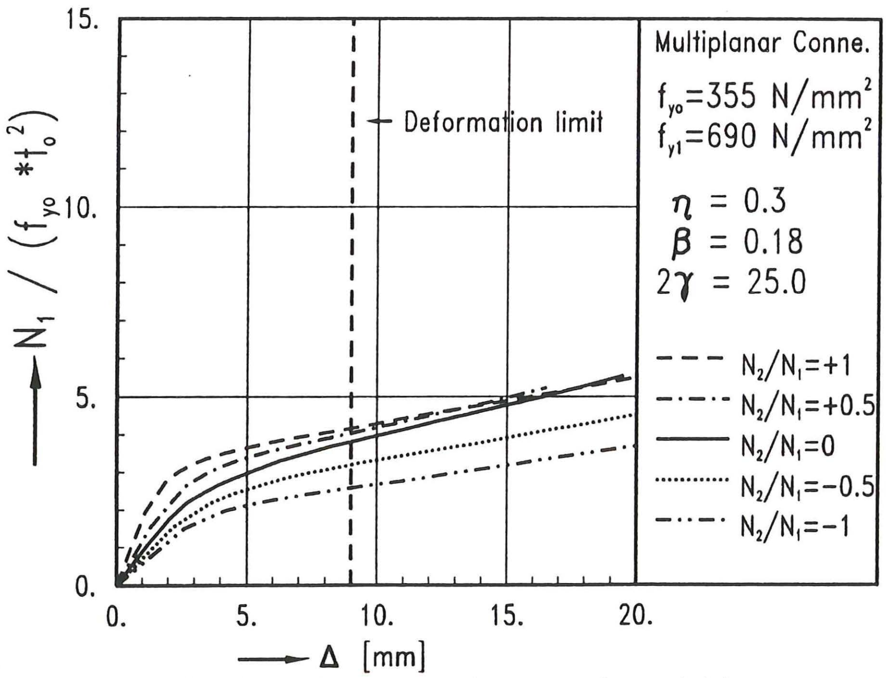


Fig. 7 Load – displacement curves for xxb14a

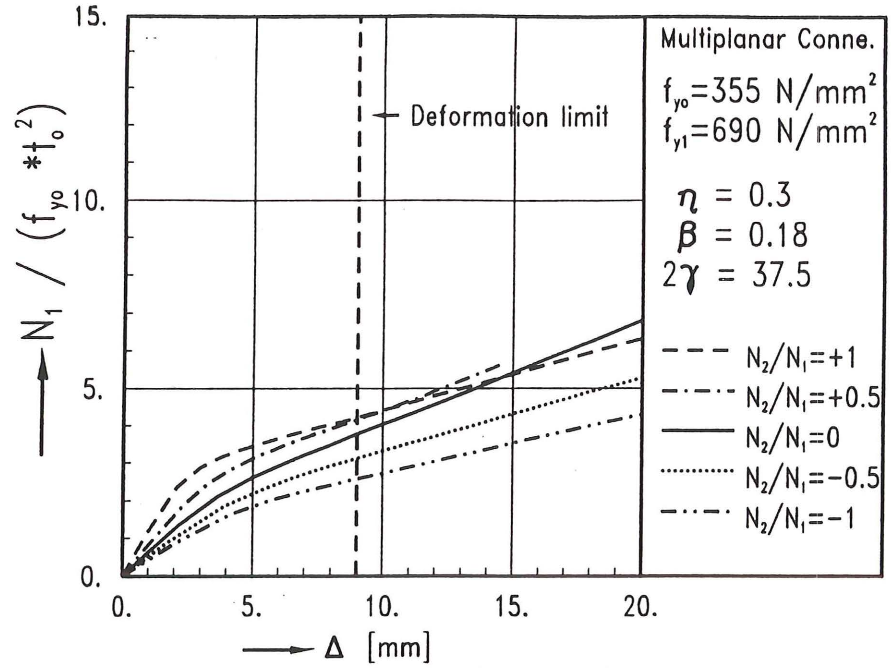


Fig. 8 Load - displacement curves for xxb15a

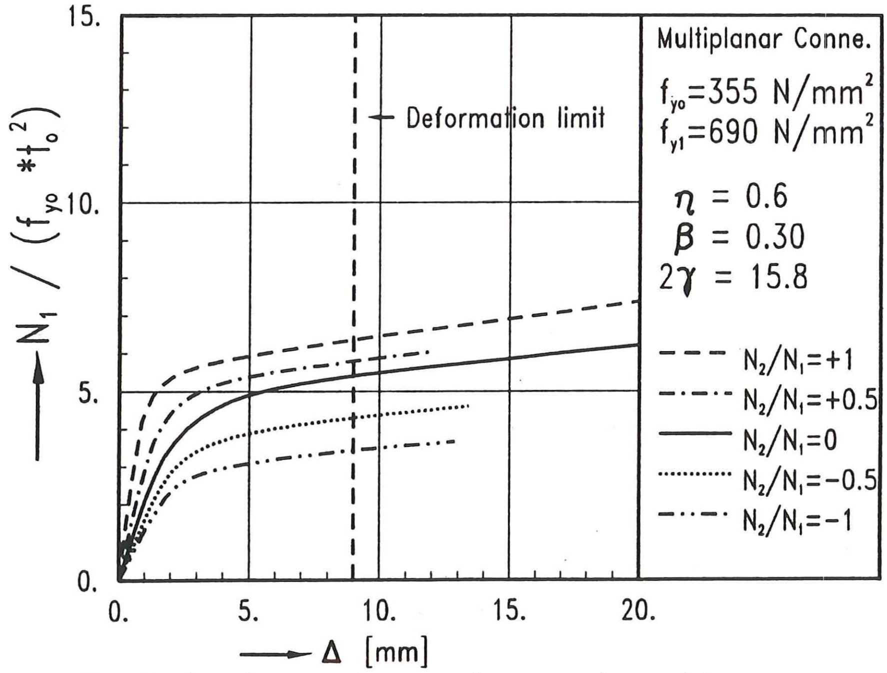


Fig. 9 Load - displacement curves for xxb1a

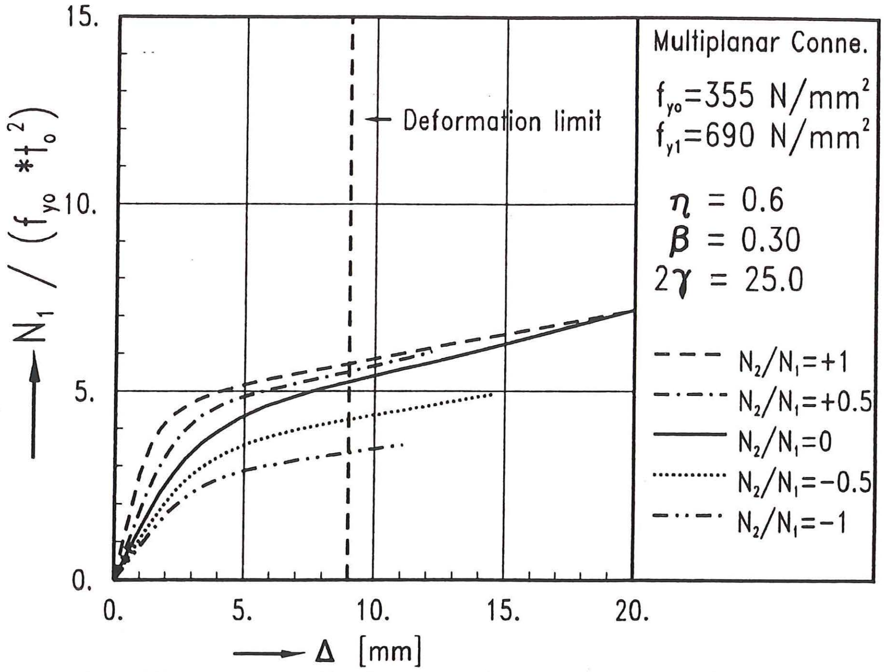


Fig. 10 Load - displacement curves for xxb2a

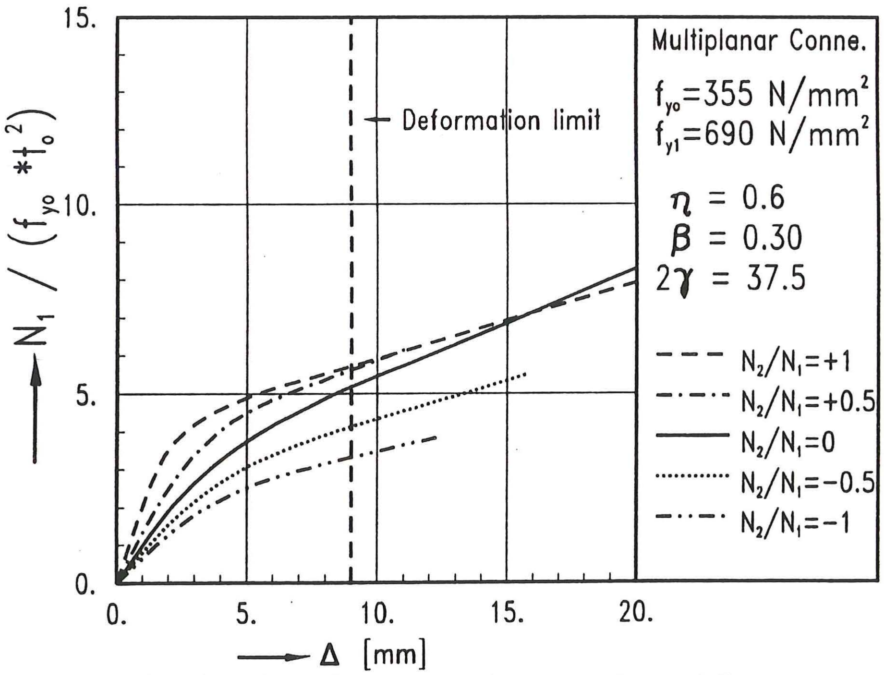


Fig. 11 Load - displacement curves for xxb3a

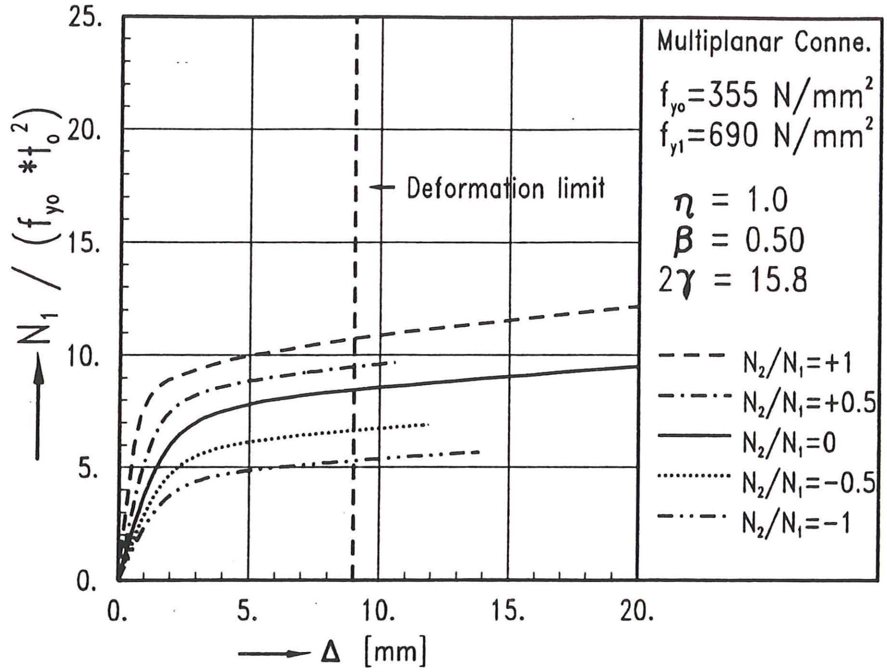


Fig. 12 Load - displacement curves for xxb4a

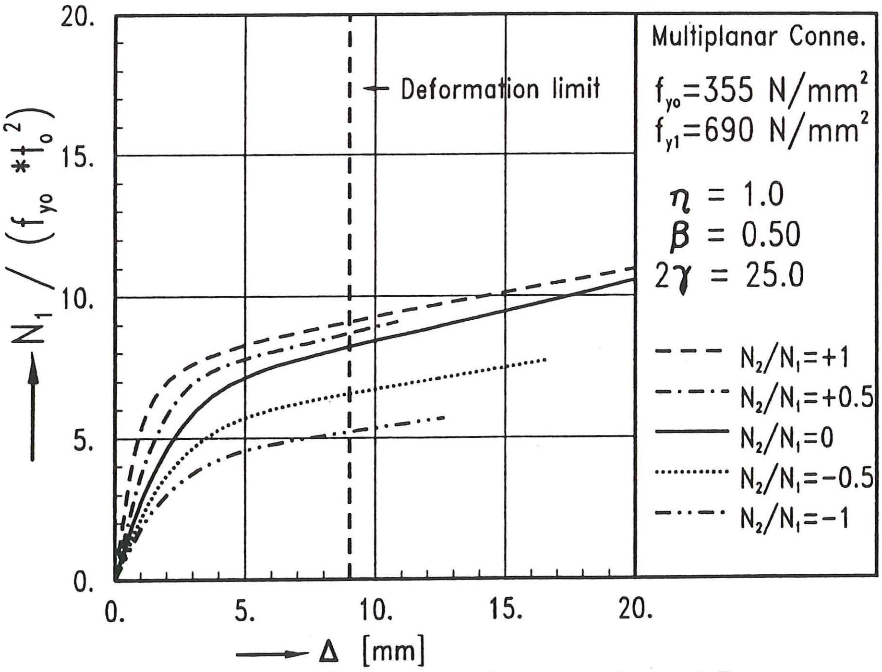


Fig. 13 Load - displacement curves for xxb5a

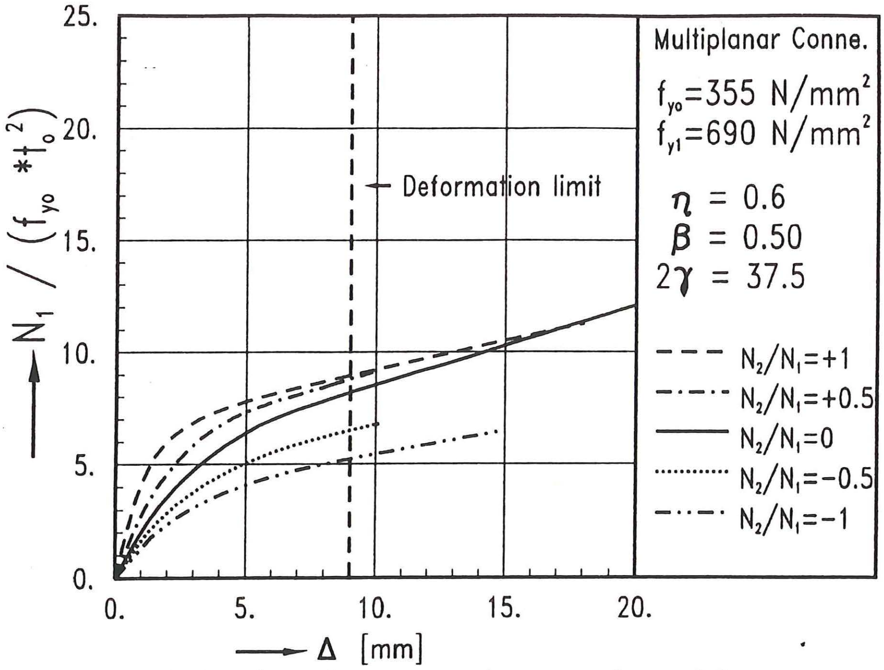


Fig. 14 Load - displacement curves for xxb6a

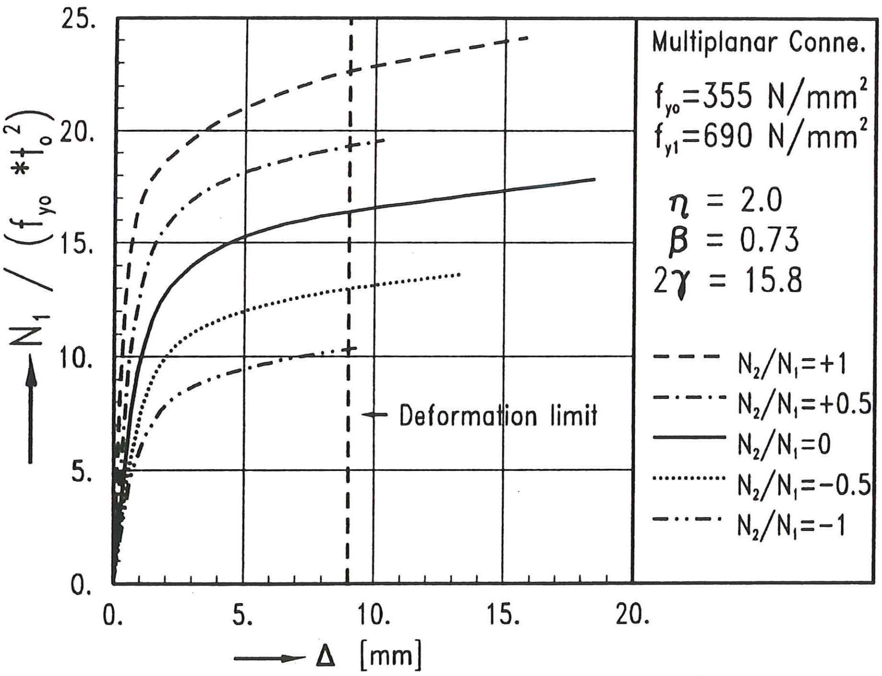


Fig. 15 Load - displacement curves for xxb7a

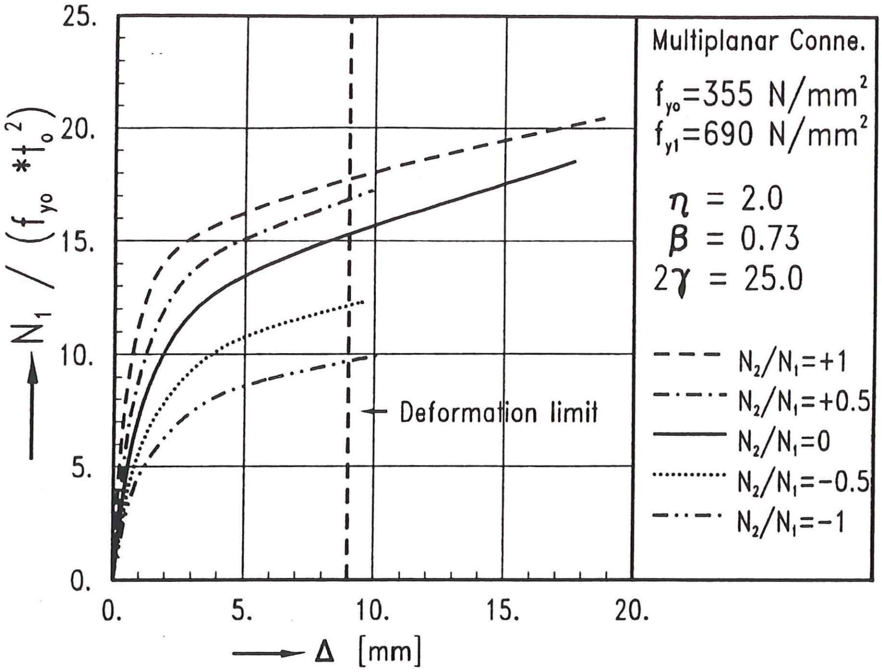


Fig. 16 Load – displacement curves for xxb8a

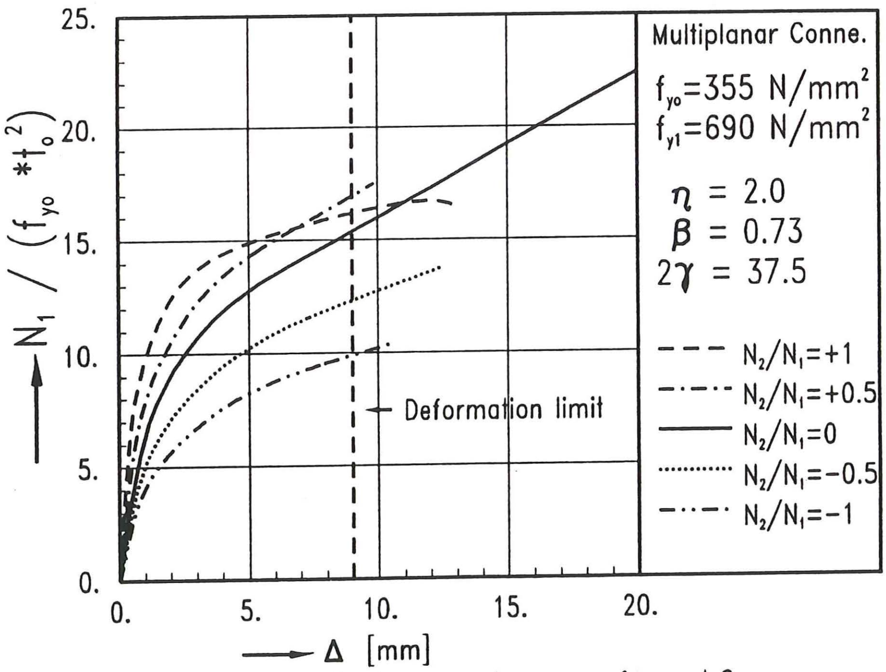


Fig. 17 Load – displacement curves for xxb9a

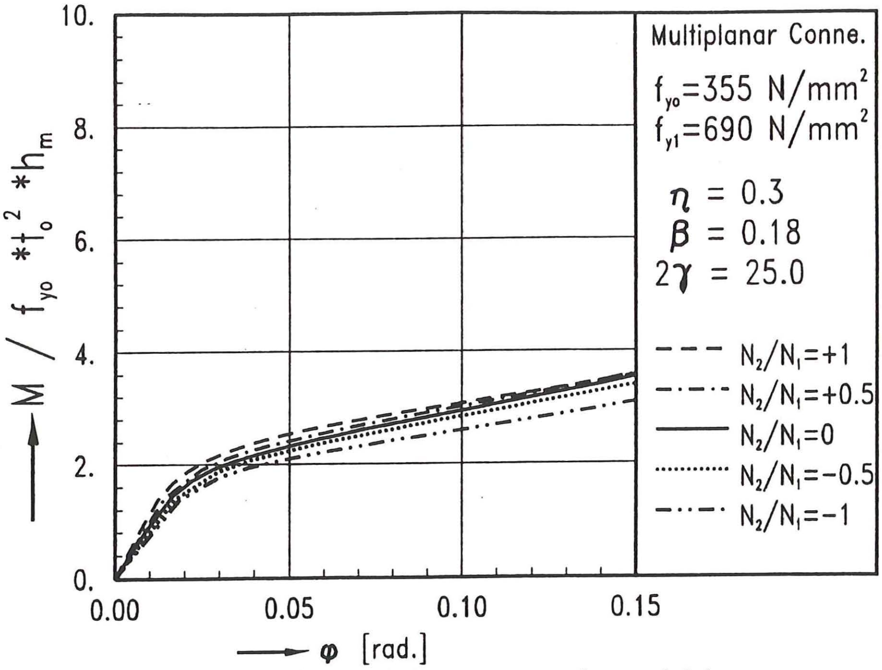


Fig. 18 Moment - rotation curves for xxb14

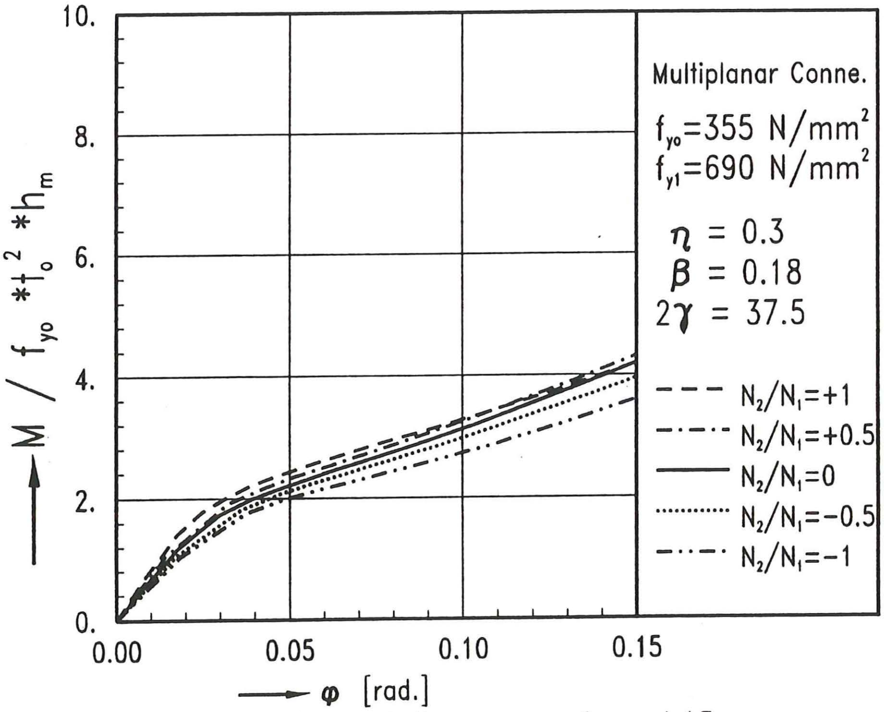


Fig. 19 Moment - rotation curves for xxb15

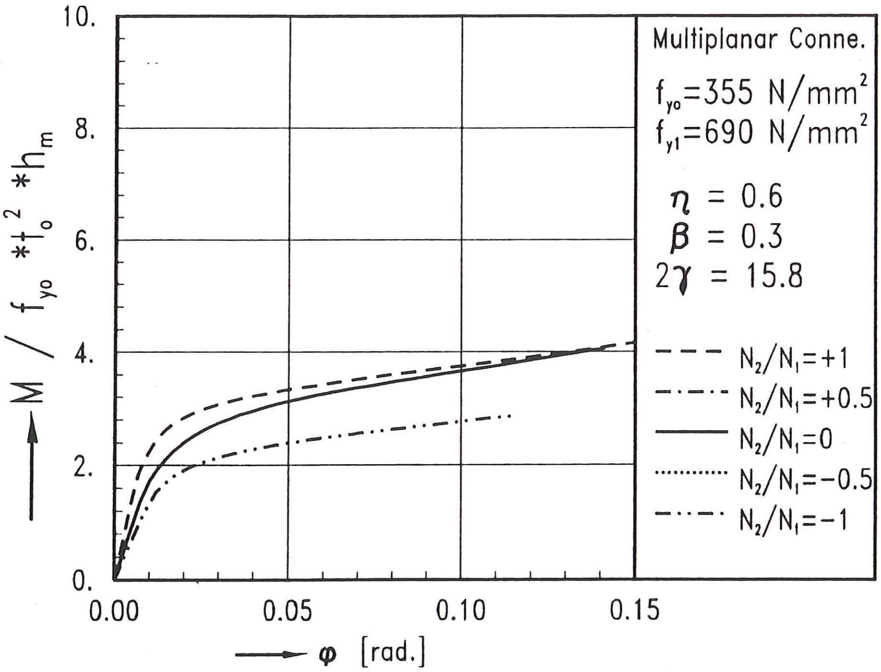


Fig. 20 Moment - rotation curves for xxb1

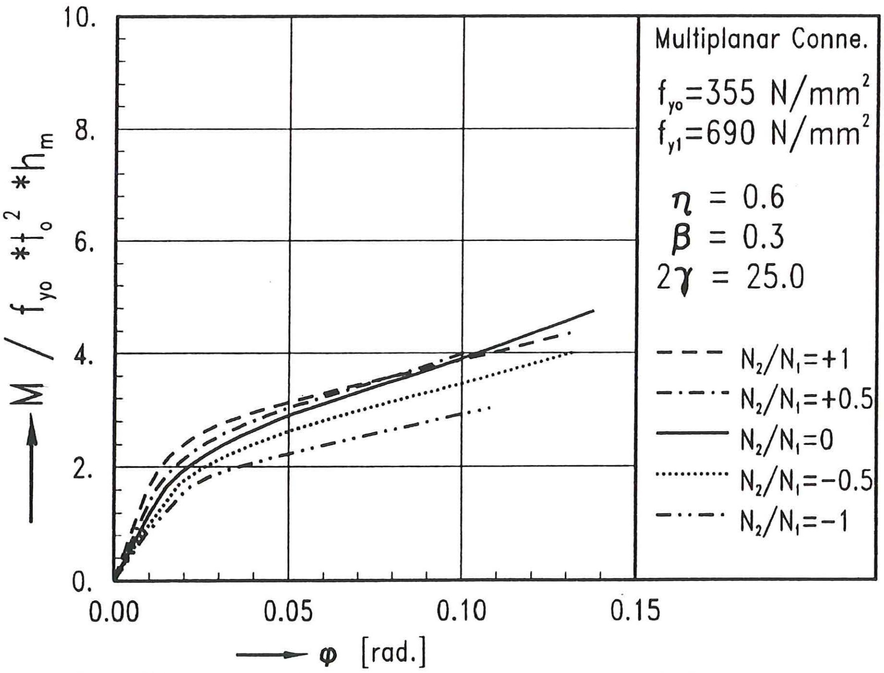


Fig. 21 Moment - rotation curves for xxb2

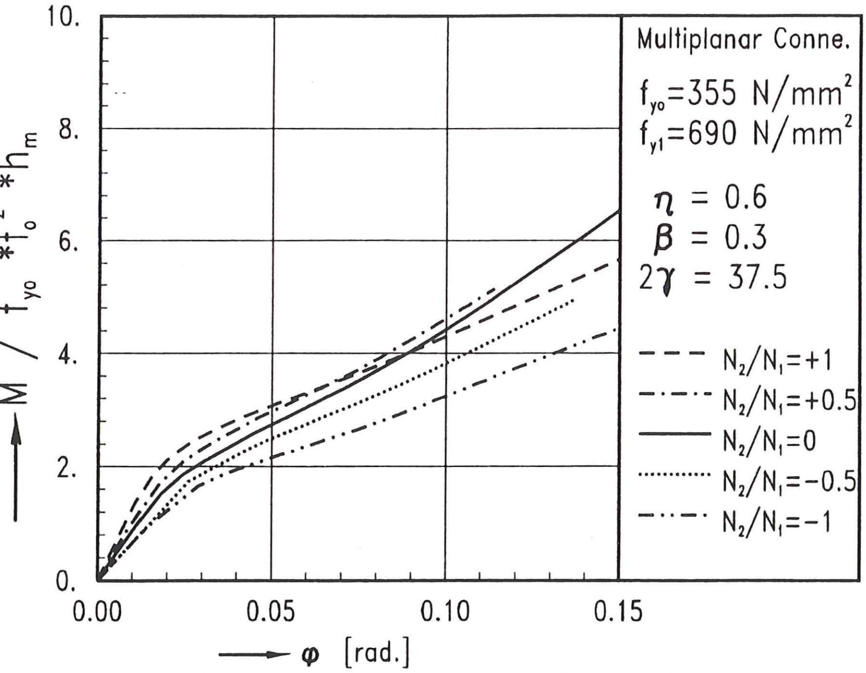


Fig. 22 Moment - rotation curves for xxb3

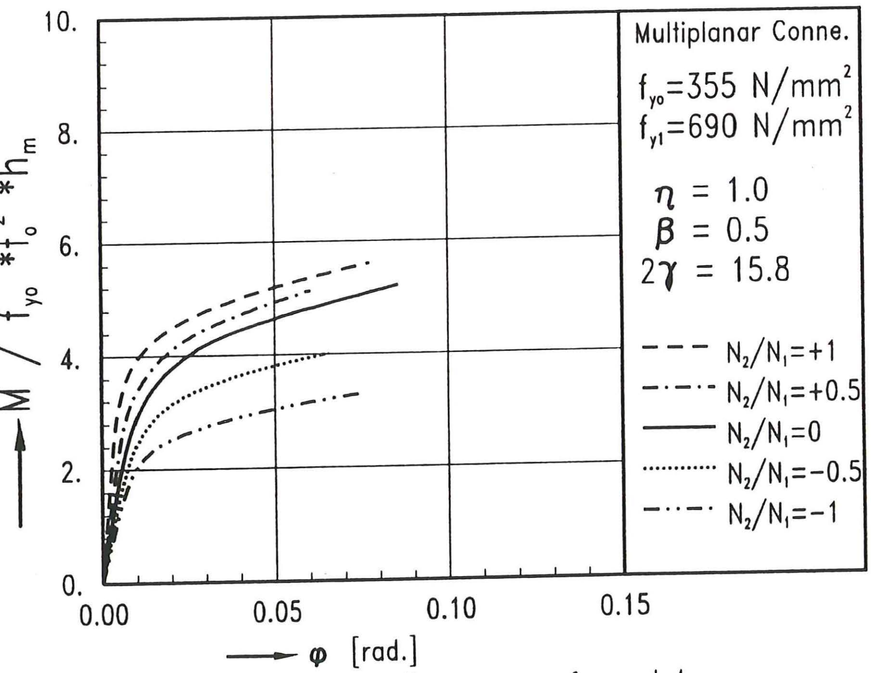


Fig. 23 Moment - rotation curves for xxb4

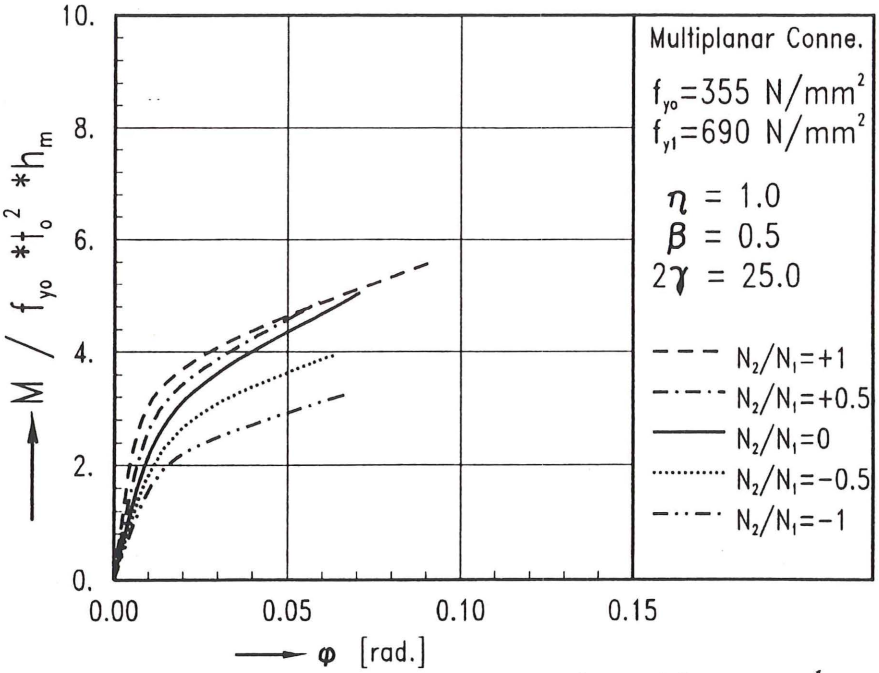


Fig. 24 Moment - rotation curves for xxb5

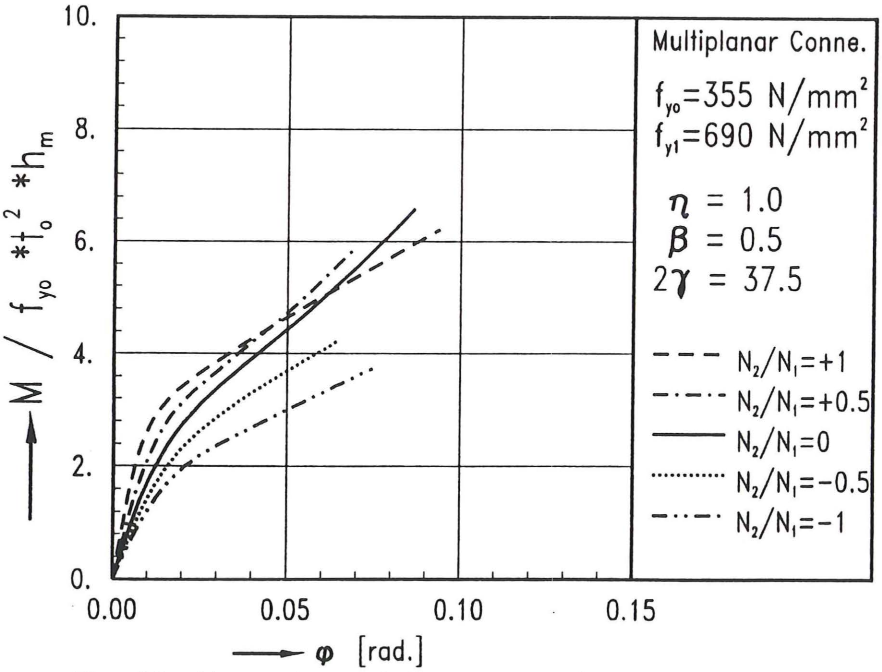


Fig. 25 Moment - rotation curves for xxb6

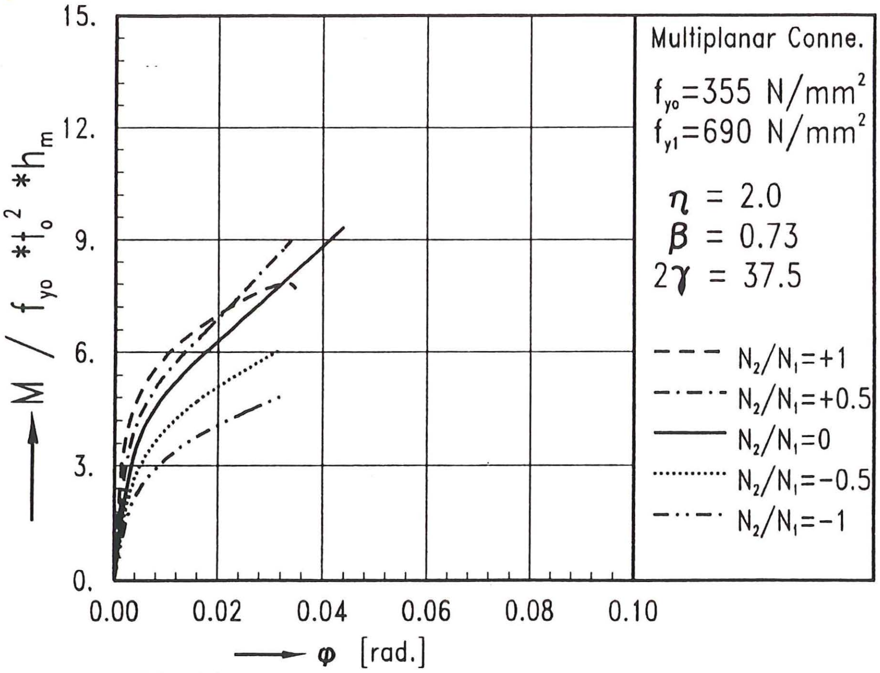


Fig. 28 Moment – rotation curves for xxb9

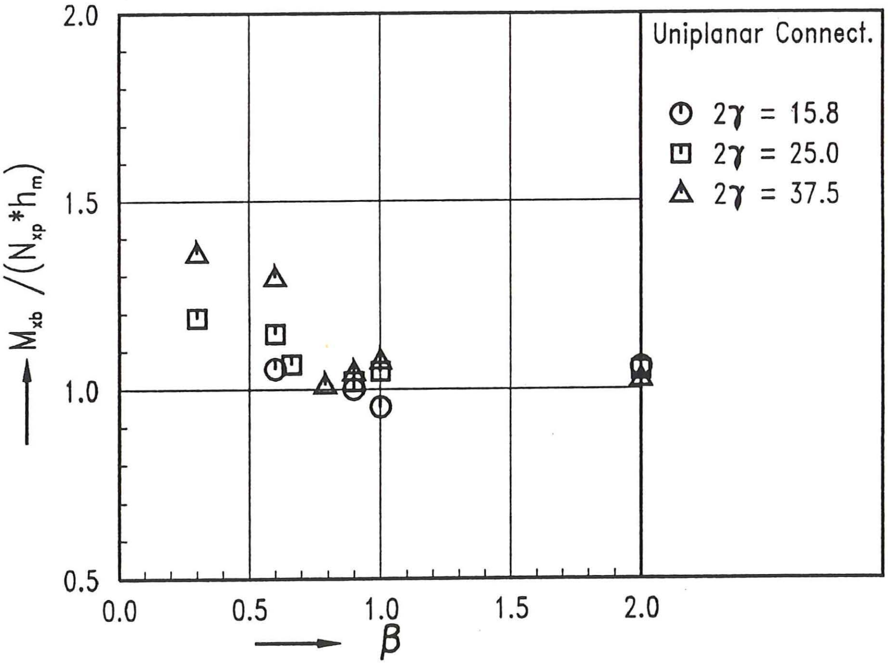


Fig. 29 Comparisons between I-beam to RHS column and corresponding plate to RHS connections

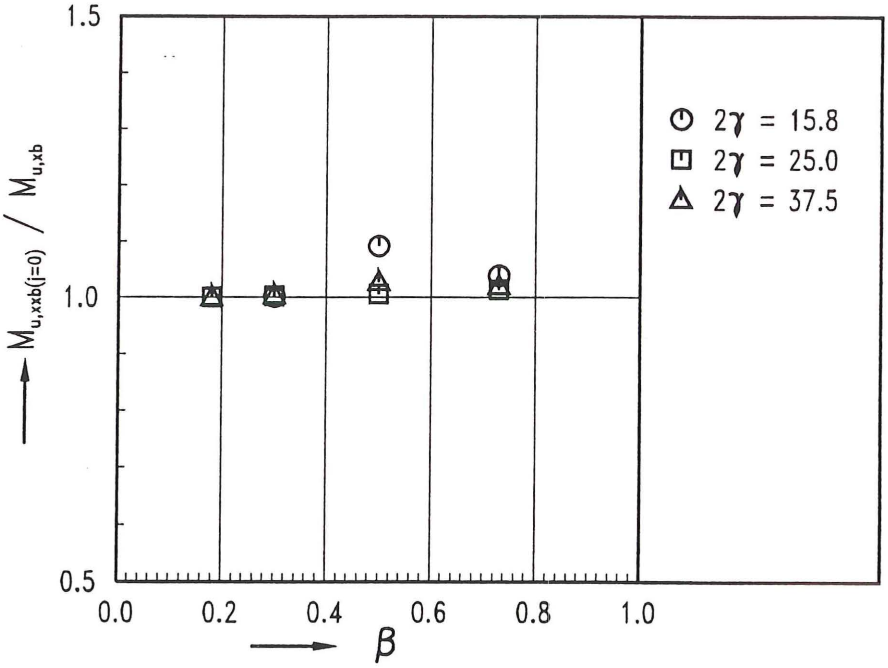


Fig. 30 Comparisons between multiplanar connections with J=0 and corresponding uniplanar connections

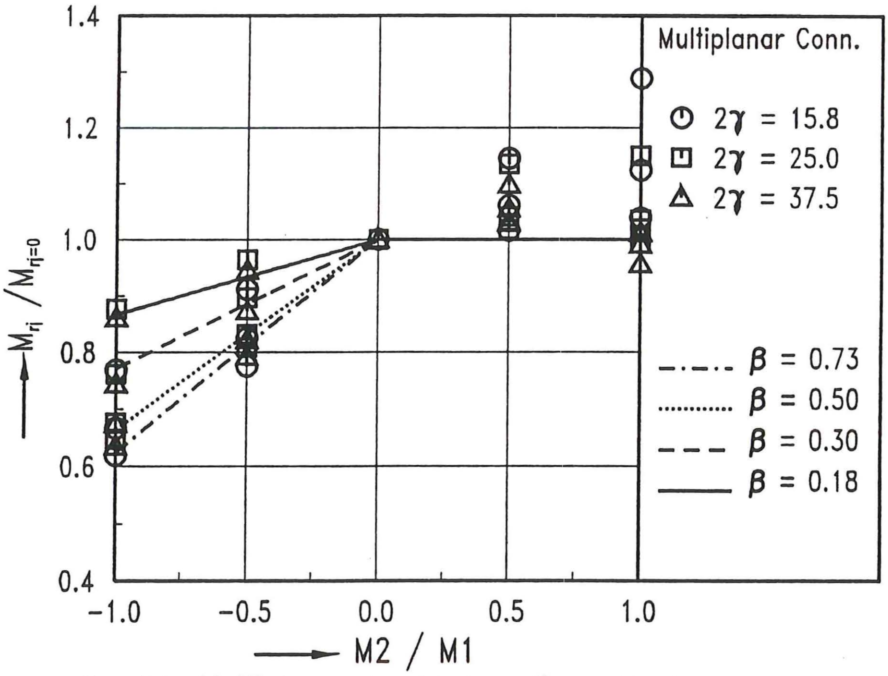


Fig. 31 Multiplanar load interaction effects

PARAMETRIC STUDY ON THE STATIC STRENGTH OF UNIPLANAR AND MULTIPLANAR PLATE TO RHS COLUMN CONNECTIONS

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ABSTRACT

Welded uniplanar or multiplanar connections between I-beams and rectangular hollow section (RHS) columns are attractive for use in offshore deck structures and industrial buildings. The static behaviour of such connections under axial loads and in-plane bending moments is mainly related to the geometrical parameters of the connection, such as the widths of plates or I-beams and columns, the thickness of the column wall and the depth of the I-beams. In order to investigate the individual influence of these components separately and to give general design formulae for static loaded uniplanar and multiplanar connections between plates or I-beams and RHS columns under different load cases, in this research work, numerical analyses has been carried out on connections between plates and rectangular hollow section columns loaded with compression on the plates. A pair of plates can be used to represent the flanges of an I-section beam to RHS column connection.

Based on analytical failure models and on the results obtained from the finite element analyses, basic strength formulae for both uniplanar and multiplanar plate to RHS column connections are given.

KEY WORDS : Uniplanar and multiplanar plate to RHS column connection, FE analyses, multiplanar load effects, basic strength formulae.

LIST OF SYMBOLS

b_0 : width of RHS column
b_1 : width of plate
l_0 : length of RHS column
l_1 : length of the plate
t_0 : wall thickness of RHS column
t_1 : thickness of plate
f_{y0} : yield stress of RHS member
f_{y1} : yield stress of plates
J : load ratio $J = N_2/N_1$
N_i : axial compression applied to the plate, $i = 1, 2$
N_{Rd} : the design strength of the connection
N_{xp} : uniplanar connection strength at a deformation limit of $3\%b_0$
N_{xxp} : multiplanar connection strength at a deformation limit of $3\%b_0$
r^2 : correlation coefficient
$R_1..R_6$: regression constants
β : width ratio between I-beam flange and RHS column b_1/b_0
2γ : width to thickness ratio of RHS column b_0/t_0
γ_m : partial safety factor for the resistance
τ : thickness ratio of I-beam and RHS column t_1/t_0
Δ : local deformation of RHS column face
RHS : rectangular hollow section
CIDECT: Comité International pour le Développement et l'Étude de la Construction Tubulaire

INTRODUCTION

From the previous research of Lu (1993a, 1993b), it has been shown that the static behaviour of multiplanar connections between plates or I-section beams and RHS columns is dependent not only on the geometrical and material parameters, but also on the loading cases. Therefore, extensive numerical investigations have been carried out to determine the connection behaviour and to establish general design formulae for these kinds of connections. Since good agreement has been found between the numerical and experimental results for connections with various geometries and loading cases, finite element analyses can be used to simulate the behaviour of the static loaded plate or I-section beam to RHS column connections.

In the present work, numerical research has been carried out on 18 uniplanar X connections and 12 multiplanar X connections. The influence of the loading cases on the multiplanar connections have been investigated by analysing each multiplanar connection with five different load ratios, J = -1, -0.5, 0, 0.5, 1.

Six β values and three 2γ values have been considered for uniplanar connections, which are β = 0.18, 0.3, 0.5, 0.73, 0.87, 0.93 and 2γ = 15.8, 25.0, 37.5. For the multiplanar connections, investigations have been carried out only for connections with $\beta \leq 0.73$, due to the way of the numerical modelling. Based on the numerical results and analytical failure models, basic strength formulae for uniplanar and multiplanar connections are suggested.

RESEARCH PROGRAMME

A total of 18 uniplanar connections and 12 multiplanar connections has been investigated by using finite element analyses. The configurations of the connections are shown in figure 1. For all connections, the width of the RHS column is kept constant, i.e. $b_0 = 300$ mm. The dimensions of the plates have been chosen such that they are in accordance with the flanges of I-section beams. For example, for connections xp1 (xxp1) to xp12 (xxp12), the plates are taken as the flanges of I-section beams to RHS column connections as presented in the paper of Lu (1994a), so that the results can be easily compared with each other to give the influence of the beam depth. The non-dimensional geometrical parameters β, 2γ and τ for the connections investigated in this paper are given in Table 1. The geometries for multiplanar connections are the same as those of the corresponding uniplanar connections with the same β and 2γ values.

Table 1 Parameters of connections between plates and RHS columns with b_0=300 mm

Uniplanar connections	Multiplanar connections	β	2γ	τ
xp1	xxp1	0.3	15.8	0.42
xp2	xxp2	0.3	25.0	0.67
xp3	xxp3	0.3	37.5	1.00
xp4	xxp4	0.5	15.8	0.56
xp5	xxp5	0.5	25.0	0.89
xp6	xxp6	0.5	37.5	1.34
xp7	xxp7	0.73	15.8	1.00
xp8	xxp8	0.73	25.0	1.58
xp9	xxp9	0.73	37.5	2.37
xp10	xxp10	0.93	15.8	0.68
xp11	xxp11	0.93	25.0	1.08
xp12	xxp12	0.93	37.5	1.62
xp13	xxp13	0.18	15.8	0.30
xp14	xxp14	0.18	25.0	0.48
xp15	xxp15	0.18	37.5	0.71
xp16		0.87	15.8	0.66
xp17		0.87	25.0	1.04
xp18		0.87	37.5	1.56

The steel grade used for all RHS column in the numerical modelling is Fe510 with a yield stress of 355 N/mm^2. In order to avoid plate failure before connection failure, a steel grade of StE 690 with a yielding stress of 690 N/mm^2 is taken for all plates. In case the plate yielding is still critical for connections by using StE 690, an artificial elastic-plastic steel grade is used with f_{y1}=5000 N/mm^2.

To investigate the influence of multiplanar loading on the connection behaviour, each of the models for multiplanar connections has been calculated with five different load cases, namely N_2/N_1 = -1, -0.5, 0, +0.5 and +1.

NUMERICAL MODELLING

For the numerical modelling, the length of the RHS column l_0 is kept to $6b_0$ =1800 mm, the length of the plate l_1 is $5b_1$. Since calibrations of the numerical models with experiments show good agreement, as already described by Lu (1993b), the parameter studies are done in the same way as in the modelling for the calibrations. Eight noded thick shell elements (MARC element type 22) have been used for connection modelling. For axially loaded plate to RHS column connections, due to symmetry in geometry and loading, only an eighth of the connection has been modelled in order to reduce the number of elements and nodes. In figure 2, typical finite element meshes are shown for a multiplanar connection.

It should be mentioned that throughout this parameter study, butt welds are considered which are stronger than the parent material being connected. Since the nominal size of the fillet part of butt welds according to AWS (1992) and Eurocode 3 (1992) is relative small, no weld elements have been modelled in the numerical models. However, the actual weld sizes are general larger than the nominal sizes, this may lead to an increase of the actual connection strength. The influence of the welds will be investigated in the near further.

During the numerical analyses, displacement control has been used for N_2/N_1 = 0 and 1. For N_2/N_1 = -1, -0.5 and +0.5, load control is used so that a fixed load ratio of the connections can be maintained even after plastic deformations.

OBSERVATIONS OF FE ANALYSES

The load (N) - displacement (Δ) diagrams obtained from the numerical analyses for the uniplanar connections are shown separately for each group of connections with the same β values, see figure 3 to 7. The influence of 2γ can be directly seen from these figures. The results for the multiplanar connections are presented in figures 8 to 19. The influence of multiplanar loading on the stiffness and strength of connection are shown clearly.

As no maximum loads have been obtained during the analyses, a deformation limit for ultimate strength of the connections taken as 3%b_0 at the intersections of plates and chord faces, as given by Lu (1994b), is used. The non-dimensional strength of connections at the deformation limit for uniplanar connections have been plotted against β in figure 20. As can be expected, the strength of the uniplanar plate to RHS column connections increases with increasing β values. But the 2γ ratio has almost no influence on the strength of the connections, especially for $\beta \leq 0.87$.

Further, the strengths of the multiplanar connections with J = 0 have been compared with the strength of the corresponding uniplanar connections. As shown in figure 21, almost no difference is found between the strength of the multiplanar connections with J = 0 and the strength of the corresponding uniplanar connections. This is different from connections with CHS columns. However, a positive load ratio (J = 0.5 and 1) causes generally an increase of the initial stiffness and the strength compared to that of the connections with J = 0. A negative load ratio (J = -0.5 and -1) leads to a reduction of the initial stiffness and the strength of the connections. This effect is shown in figure 22.

CONSIDERATION OF FAILURE MODES

From the experiments, it has been observed that several failure modes can be obtained for axially tension loaded plate to RHS column connections, namely chord face yielding, punching shear, chord side wall failure, and brace effective width failure mode (Wardenier, 1982 and Packer, 1992). Comparing the formulae for these failure modes given by the CIDECT design guide with each other shows that the effective width failure governs always. However, when the connections are loaded in compression, the brace cracking will not occur, but local plate buckling is likely to occur. It can be concluded that for compression loaded connections between plates and RHS columns, three failure modes should be considered, namely chord face yielding, chord face punching shear and chord side wall failure for $\beta = 1.0$.

Since in the numerical modelling, cracks can not yet be modelled, punching shear failure can not be checked numerically. Only chord face yielding and chord side wall failures are observed. From the post-processing of the numerical modelling, it is found that for the connections with $\beta \leq 0.87$, the failures of the connections are caused by the chord face yielding, while for $\beta = 0.93$, chord side wall failures occur. The design formulae for punching shear and chord side failure given by the CIDECT design guide for tension loaded connections are based on experiments and can be used as a general check. For comparison, the numerically determined connection strength for uniplanar connections and the CIDECT design formulae for punching shear and chord side wall failure have been plotted in figure 20. Also the analytical chord face yield strength line is given in this figure. For information only, the experimental results for connections 1R1 and 1R3 which have been presented by Lu (1993b) are also given in figure 20 in solid symbols. For the evaluation of the numerical results to design value, it is proposed to use a $\gamma_m = 1.0$, because of the strength limitation based on a deformation criterion and the available deformation capacity. Further, the COV is rather small and the numerically determined strength are somewhat lower then the experiments due to the negligence of the weld sizes.

As shown in figure 20, the numerically determined connection strengths are lower then those of the design lines. However, it should be noted that the design lines have been based on tension loaded specimens with fillet welds. Due to the larger weld sizes the strength of the connections is higher then those obtained numerically. Further, tension loaded specimen generally shows a somewhat higher strength then compression loaded specimen.

To determine a representative strength formulae for connections loaded by compression, regression analyses have been used.

REGRESSION ANALYSES FOR UNIPLANAR CONNECTIONS

From the numerical analyses, it is found that for connection xp13, with very small β combining low 2γ and τ values, plate failure occurs before connection failure. Therefore a yield stress of f_{y1}=5000 N/mm^2 has been used for plates instead of f_{y1}= 690 N/mm^2, as used for the other connections in the finite element analyses. For regression analysis this data point is not taken into account.

Based upon the numerical results and the chord face yielding model for axially loaded uniplanar plate to RHS column connections, which is given as :

$$\frac{N_{Rd}}{f_{y0}\, t_0^2} = \frac{4}{\sqrt{1-\beta}} \tag{1}$$

a regression model is developed

$$\frac{N_{Rd}}{f_{y0}\, t_0^2} = (R1 + R2\ \beta + R3\ \beta^2)\frac{4}{\sqrt{1-R4\beta}} \tag{2}$$

Making use of a non-linear regression analysis program, regression constants R1 to R4 are obtained. The finally determined regression results are given in Table 2. A good agreement is obtained between the numerically determined strength and the regression design line. Equation (3) can be used as a basic strength formula for uniplanar plate to RHS column connections loaded in compression.

$$\frac{N_{Rd}}{f_{y0}\, t_0^2} = (0.5 + 0.7\beta)\ \frac{4}{\sqrt{1-0.9\beta}} \tag{3}$$

This formula is plotted in figure 20. As shown in figure 20, the chord side wall failures give lower strength for connections with $\beta \geq 0.93$ then those given by formula (3), therefore, the strength of formula (3) should be limited by equation (4) for chord side wall failure :

$$\frac{N_{Rd}}{f_{y0}\, t_0^2} = 2\tau + 10 \tag{4}$$

Table 2 Results of regression analyses for uniplanar plate to RHS connections

R1	0.5	
R2	0.7	
R3	0.0	
R4	0.9	
No. of data points		17
Mean norm. errors		0.988
Correlation coefficient r^2		0.971
Coefficient of var. COV		0.039

REGRESSION ANALYSES FOR MULTIPLANAR CONNECTIONS

As already shown in figure 21, for multiplanar plate to RHS column connections with only one set of plates loaded in compression, almost no difference in strength is found between uniplanar and multiplanar connections. Therefore, for multiplanar connections with J = 0, formula (3) is used for regression analysis. Similar to xp13, the results for xxp13 are not used in the regression analysis. The results of the regression analysis are given in Table 3. Also a good agreement is found.

Table 3 Results of regression analyses for multiplanar connections with $N_2/N_1=0$

No. of data points	11
Mean norm. errors	1.016
Correlation coefficient r^2	0.991
Coefficient of var. COV	0.026

The influence of the multiplanar loading on two sets of plates is shown in figure 22. On the vertical axis, the strength ratio between connections loaded with J≠0 and connections loaded with J=0 is given. It can be seen that when the connections are loaded with positive load ratios, the connection strengths increase in most cases except for connection xxp9 with J = 1. In this case, because of the large β and large 2γ values, the corner area of the chord fully yields and deforms to the outside. The increase of the connection strength with positive load ratio is more pronounced for connection with small β value. For negative load ratios, the connection strength decreases significantly.

To describe this multiplanar loading influence, the following regression model is assumed:

$$\frac{N_{J\neq 0}}{N_{J=0}} \; 1 + J(R1 + R2\beta + R3\beta^2) \; + J^{\,2}(R4 + R5\beta + R6\beta^2) \tag{5}$$

where $J = N_2/N_1$.

It should be mentioned that for connection xxp7 with the same β and load ratio as for xxp9, due to the large β and small 2γ ratio, the transfer of force is more directly by the axial stresses in the corner. As a consequence, the strength of the connection is mainly determined by the plates. Therefore the result for xxp7 with J = 0 is not used in the regression analysis.

The finally determined regression results are given in Table 4. The influence of multiplanar loading applied to multiplanar connections can be described by equation (6) :

$$\frac{N_{j\neq 0}}{N_{j=0}} = 1 + 0.2J - 0.2\beta J^2 \tag{6}$$

Table 4 Results of regression analyses for multiplanar loading influence

R1	0.2	
R2	0.0	
R3	0.0	
R4	0.0	
R5	-0.2	
R6	0.0	
No. of data points		54
Mean norm. errors		0.984
Correlation coefficient r^2		0.987
Coefficient of var. COV		0.03

Formula (6) is plotted in figure 22 for four β values.

CONCLUSIONS

Based on the results of the FE analyses and regression analyses the following conclusions can be drawn :

- For plate to RHS column connections loaded by axial compression, the failure of the connections with β ≤ 0.87 is mainly determined by local failure of the chord face, while for connections with β ≥ 0.93, it is related to chord side wall failure.
- The influence of unloaded out-of-plane plates on multiplanar connections is negligible in comparison to a similar uniplanar connection.
- The strengths of the multiplanar connections are increased by the positive load ratios. But this effect becomes smaller when the β values increase.
- The strengths of the multiplanar connections are reduced by the negative load ratio, this effect becomes stronger with larger β values because the restraints of the corners are reduced.

- Equation (3) can be used as a basic strength formula for butt welded uniplanar and multiplanar plate to RHS column connections with $\beta < 0.93$ loaded in compression. However, it may be conservative for connections with fillet welds. Further, the chord side wall failure criterion gives a lower strength for $\beta \geq 0.93$, the strength of formula (3) should be limited by formula (4).
- The multiplanar loading effect on the multiplanar connections can be described by equation (6).

Uniplanar connection Chord face yielding : $\frac{N_{Rd,xp}}{f_{y0}\, t_0^2} = (0.5+0.7\beta)\frac{4}{\sqrt{1-0.9\beta}}$ Chord side wall failure : $\frac{N_{Rd,xp}}{f_{y0}\, t_0^2} = 2\tau + 10$
Multiplanar connection $N_{Rd,xxp} = N_{Rd,xp}$ For $J = 0$ $N_{Rd,xxp} = f(J)\, N_{Rd,xp}$ For $J \neq 0$ $f(J) = 1 + 0.2J - 0.2\beta J^2$

ACKNOWLEDGEMENTS

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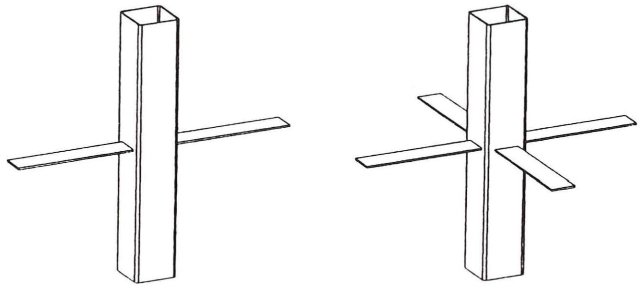

Figure 1 Configurations of plate to RHS column connections

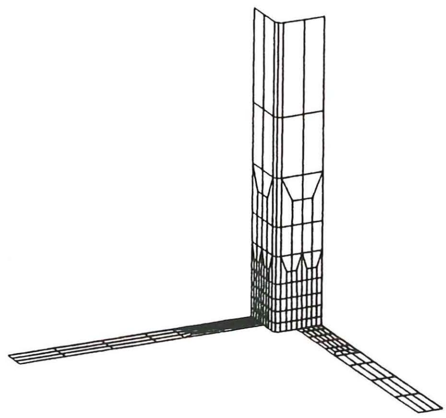

Figure 2 Typical Finite element meshes for a multiplanar connection xxp5

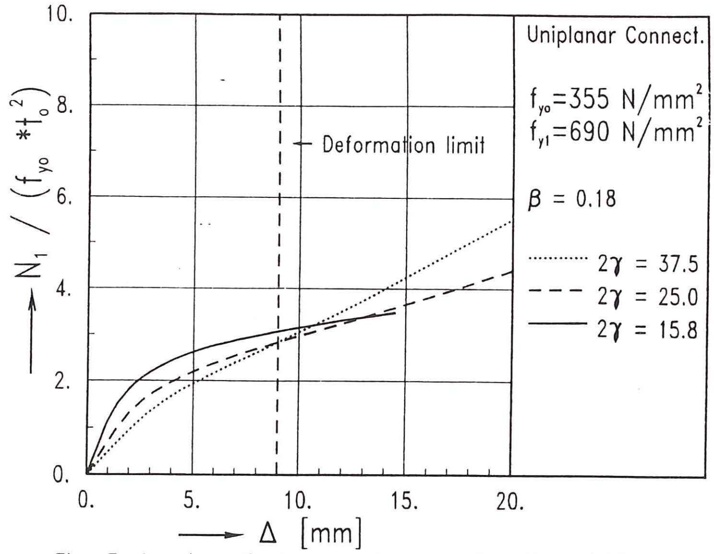

Fig. 3 Load - displacement curves for β = 0.18

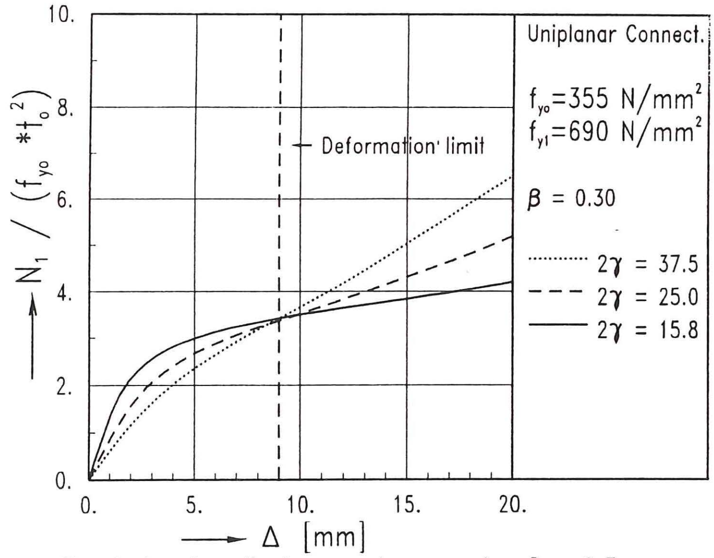

Fig. 4 Load - displacement curves for β = 0.3

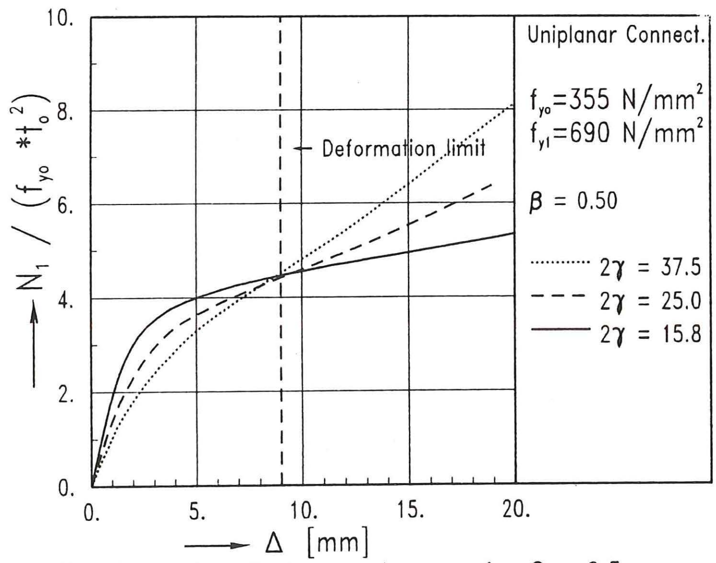

Fig. 5 Load - displacement curves for β = 0.5

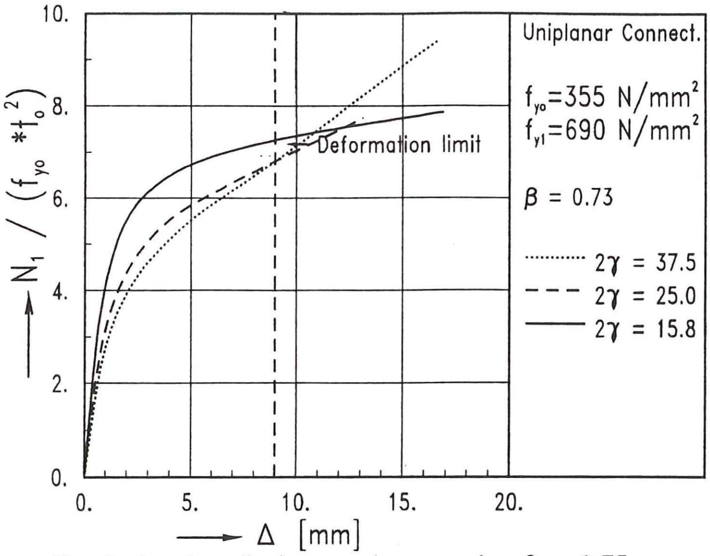

Fig. 6 Load - displacement curves for β = 0.73

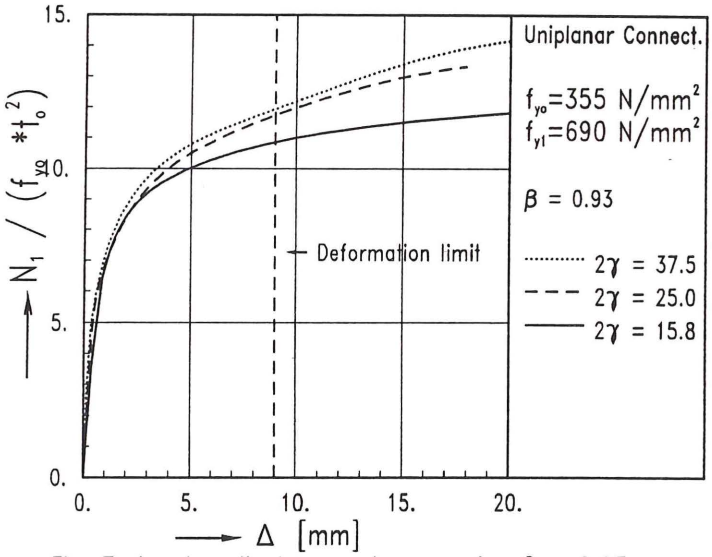

Fig. 7 Load - displacement curves for β = 0.93

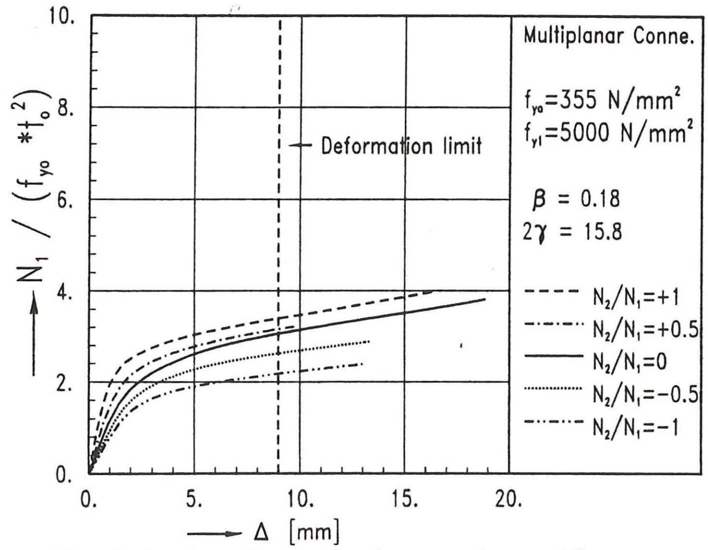

Fig. 8 Load - displacement curves for xxp13

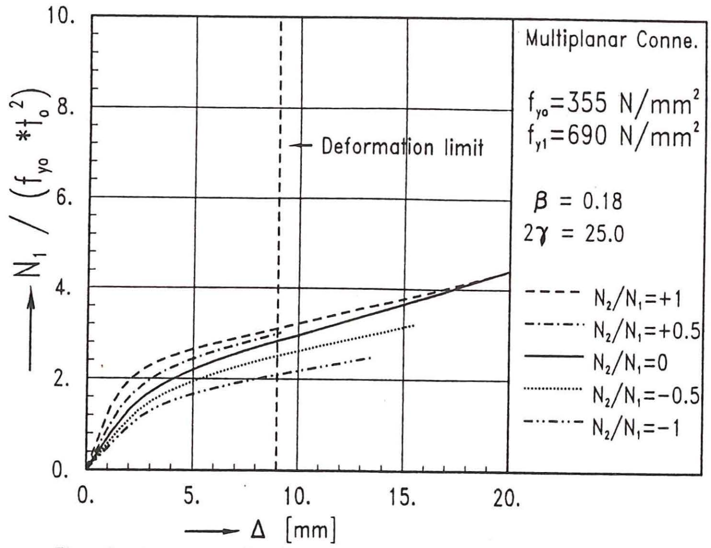

Fig. 9 Load – displacement curves for xxp14

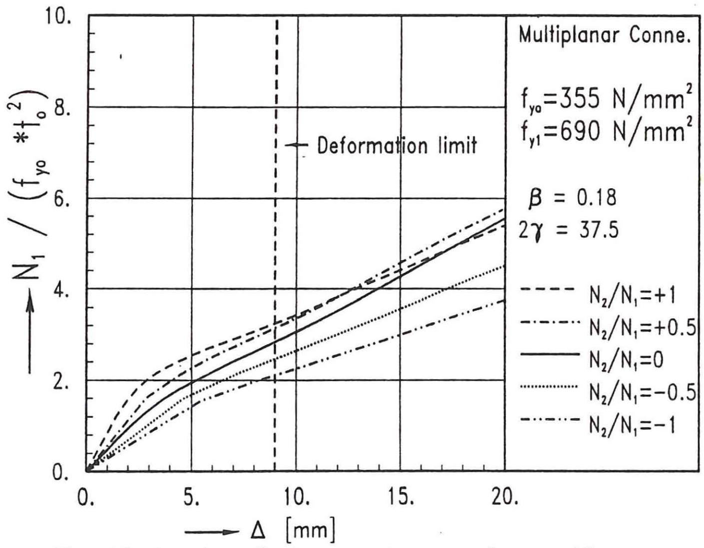

Fig. 10 Load – displacement curves for xxp15

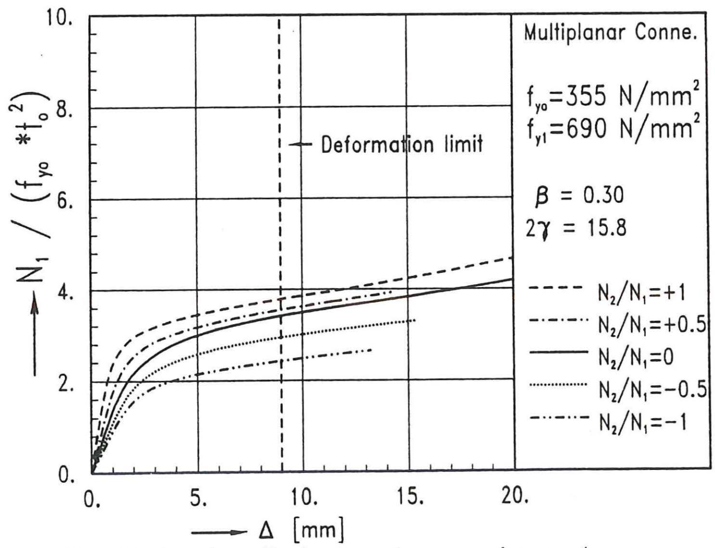

Fig. 11 Load – displacement curves for xxp1

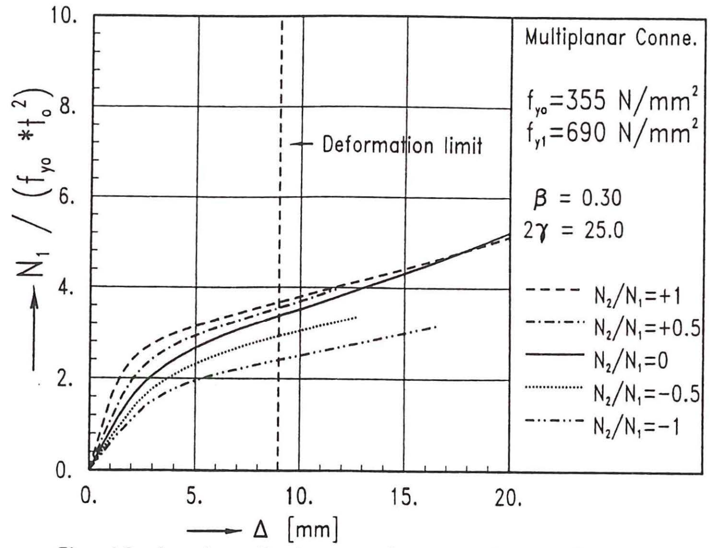

Fig. 12 Load - displacement curves for xxp2

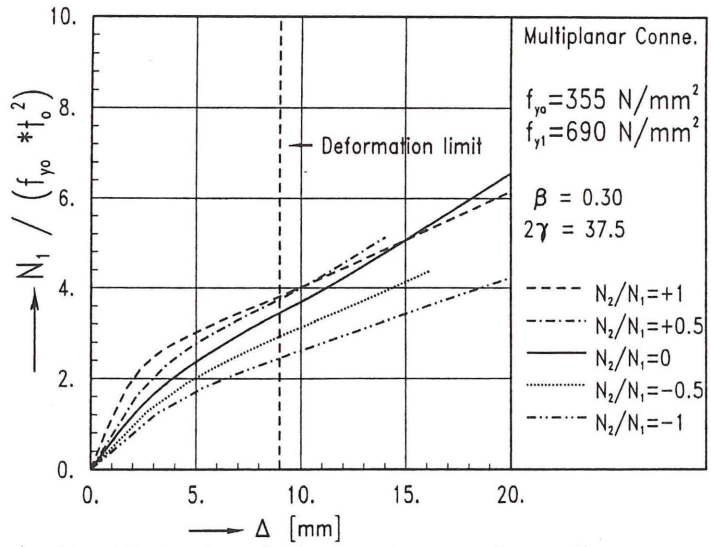

Fig. 13 Load - displacement curves for xxp3

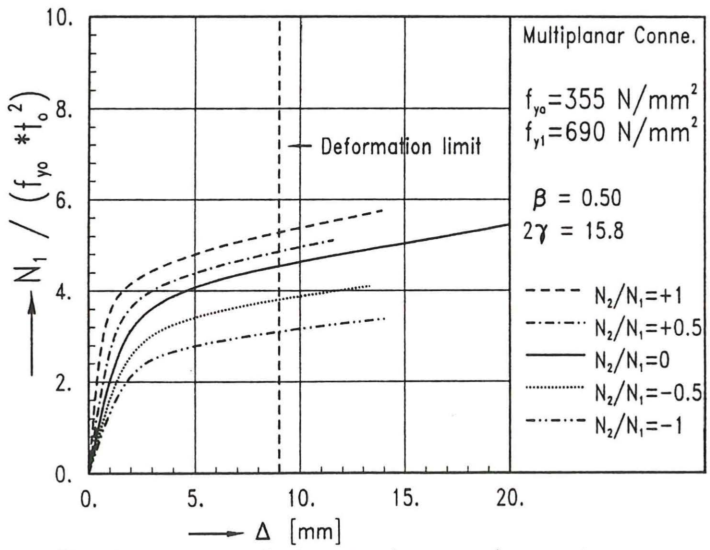

Fig. 14 Load - displacement curves for xxp4

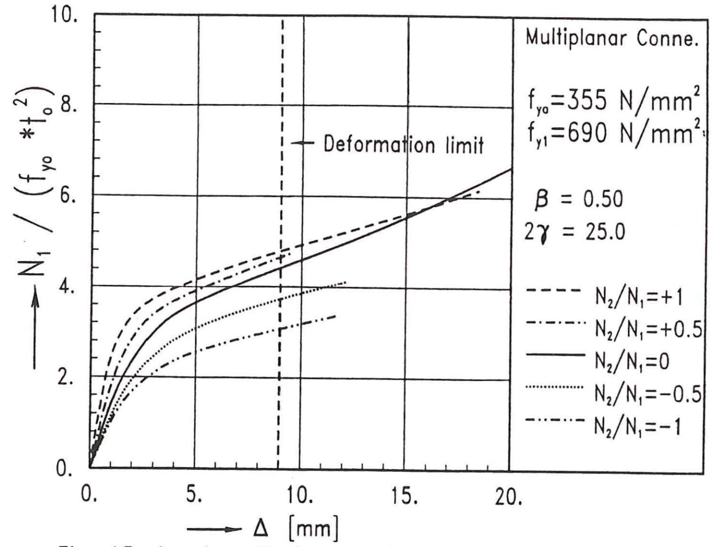

Fig. 15 Load - displacement curves for xxp5

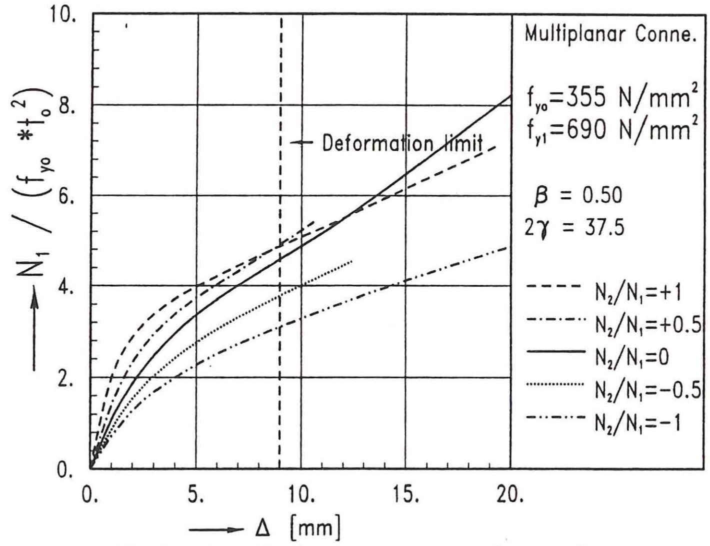

Fig. 16 Load - displacement curves for xxp6

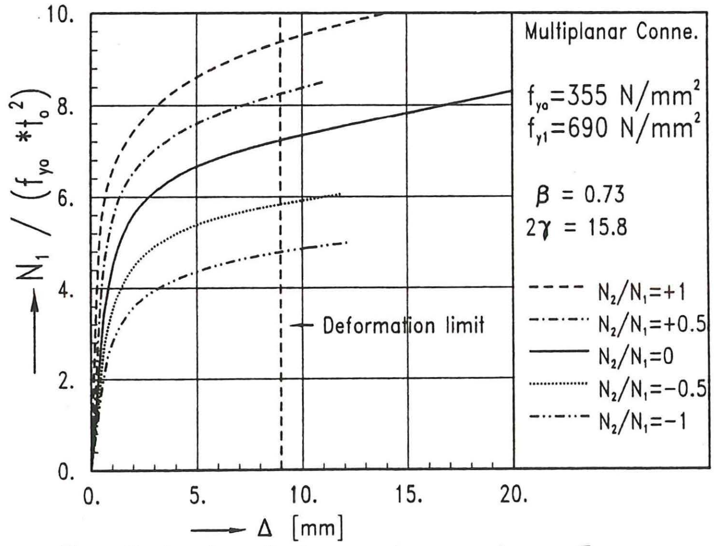

Fig. 17 Load - displacement curves for xxp7

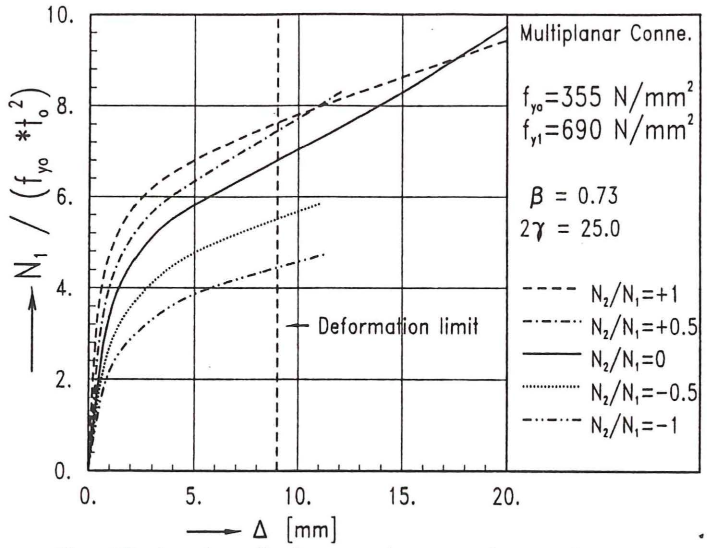

Fig. 18 Load - displacement curves for xxp8

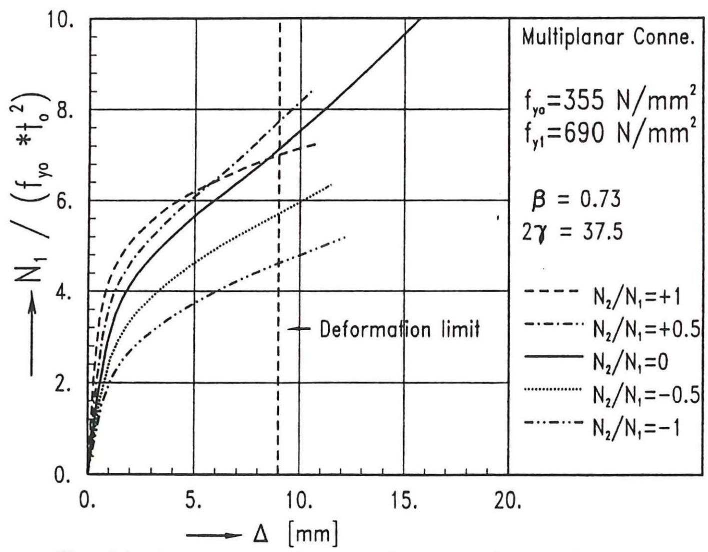

Fig. 19 Load - displacement curves for xxp9

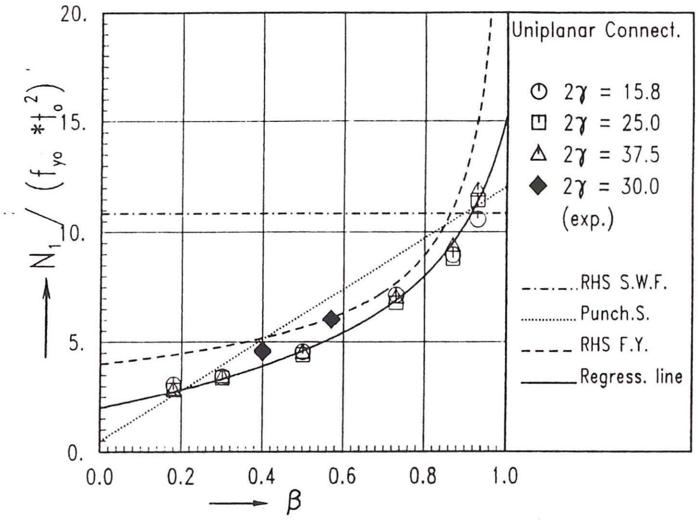

Fig. 20 The influence of β on the strength of uniplanar plate to RHS connections

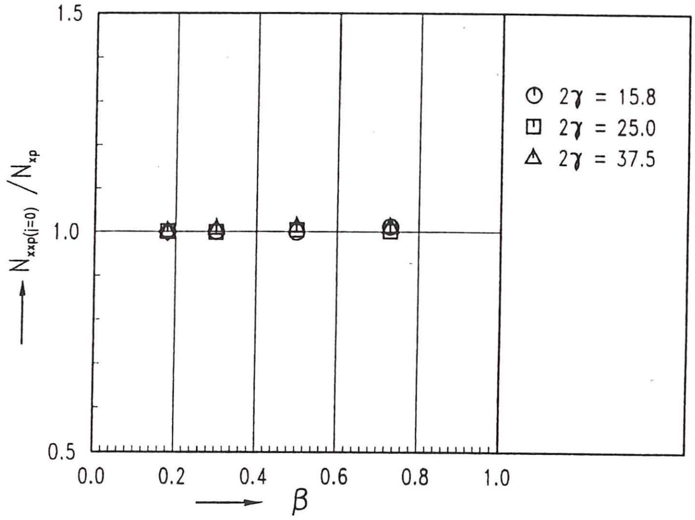

Fig. 21 Comparisons between multiplanar connections with J=0 and corresponding uniplanar connections

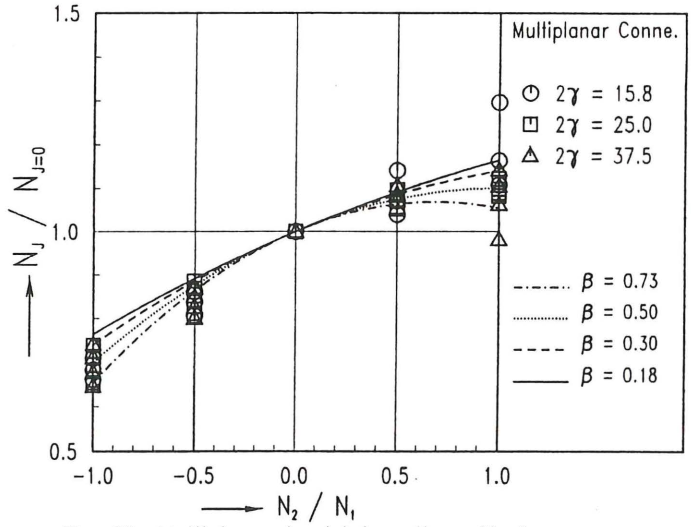

Fig. 22 Multiplanar load interaction effects

Appendix 2 :

Paper to be presented at the 14th International Conference on Offshore Machanics and Arctic Engineering

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THE STATIC STRENGTH OF UNIPLANAR AND MULTIPLANAR I-BEAM TO RHS COLUMN CONNECTIONS LOADED BY AXIAL COMPRESSION

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THE STATIC STRENGTH OF UNIPLANAR AND MULTIPLANAR CONNECTIONS BETWEEN I-BEAMS AND RHS COLUMNS LOADED BY AXIAL COMPRESSION

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ABSTRACT

This study is a part of a large project on semi-rigid connections between I-beams and RHS columns in which various geometries and load combinations are being investigated. In this paper, the results of a parameter study on connections between I-section beams and rectangular hollow section columns loaded by axial compression on the beams are presented. Fourteen uniplanar connections and eleven multiplanar connections have been investigated. The most important geometrical parameters which determine the connection strength and behaviour have been studied. Five load ratios are considered for each multiplanar connection so that the multiplanar load effects are obtained. By comparing the results from the present research and the numerical results of previous research on the corresponding connections with one level of plates to RHS columns, the influence of the second flange and web of an I-beam on the behaviour of the connections is determined. Based on the analytical models and the numerical results, strength formulae for both uniplanar and multiplanar I-beam to RHS column connections loaded by axial compression are derived.

KEY WORDS : Uniplanar and multiplanar I-beam to RHS column connection, FE analyses, multiplanar load effects, interaction of I-beam flanges, strength formulae.

LIST OF SYMBOLS

b_0 : width of RHS column
b_1 : width of I-beam's flange
h_1 : height of I-beams
t_0 : wall thickness of RHS column
t_1 : thickness of I-beam's flange
f_{y0} : yield stress of RHS member
f_{y1} : yield stress of I-beams
f(J) : multiplanar load effect function
$f(\beta,\eta)$: effect of the second flange and web of an I-beam
J : load ratio on multiplanar connections $J = N_2/N_1$
N_i : axial compression load applied to the I-beams, i =1, 2
$N_{u,xb}$: uniplanar I-beam to RHS column connection strength at a deformation limit of 3%b_0
$N_{u,xxb}$: multiplanar I-beam to RHS column connection strength at a deformation limit of 3%b_0
$N_{u,xp}$: uniplanar plate to RHS column connection strength at a deformation limit of 3%b_0
β : width ratio between I-beam's flange and RHS column b_1/b_0
2γ : width to thickness ratio of RHS column b_0/t_0
η : I-beam depth to RHS column width ratio $h1/b_0$
τ : thickness ratio of I-beam's flange and RHS column t_1/t_0
Δ : local deformation at RHS column face
RHS : rectangular hollow section
CIDECT: Comité International pour le Développement et l'Étude de la Construction Tubulaire
ECSC : European Coal and Steel Community

INTRODUCTION

Welded connections between I-section beams and RHS columns are attractive for use in offshore deck structures and industrial buildings. However, no sufficient information is available for such connections. An extensive research programme is therefore being carried out to investigate the static behaviour of these connections, including plate to RHS column connections loaded with axial compression on plates, I-beam to RHS column connections loaded with axial compression or in-plane bending moments on the I-beams.

From the previous experimental and numerical research, it has been shown that the static behaviour of the multiplanar connections between I-section beams and RHS columns is not only dependent on the geometrical parameters of the connections, such as β (width ratio between I-beam flange and RHS column b_1/b_0), 2γ (width to thickness ratio of RHS column b_0/t_0), η (I-beam depth to RHS column width ratio $h1/b_0$) etc, but also on the load interaction between two sets of the I-beams. In order to determine the individual influence of the most important geometrical parameters as mentioned above and to describe the multiplanar load effects, parametric research is carried out.

Since good agreements have been obtained between numerical and experimental results, parametric studies are carried out using finite element analyses because of the economical benefits.

The results for plate to RHS column connections have been presented by Lu (1995). In the present paper, the results of the parameter studies on I-beam to RHS column connections loaded with axial compression on I-beams are discussed. Comparisons between these two types of the connections have been made, so that the interaction of the I-beam's flanges is shown clearly.

Based on the numerical results, strength formulae for I-beam to RHS column connections loaded with compression are developed.

RESEARCH PROGRAMME

The present research programme consists of 14 uniplanar connections and 11 multiplanar connections. The non-dimensional geometrical parameters β, 2γ, τ and η for the connections investigated in this paper are given in table 1.

For all connections, the width of the RHS column is $b_0 = 300$ mm. Five β values and three 2γ values have been considered for the uniplanar connections, which are $\beta = 0.18, 0.3, 0.5, 0.73, 0.93$ and $2\gamma = 15.8, 25.0, 37.5$. For the multiplanar connections, investigations have been carried out only for connections with $\beta \leq 0.73$, due to the way of the numerical modelling.

To determine the individual influence of the η values, extra calculations have been performed on the uniplanar connections with $2\gamma = 25$ with six different η values, as shown in table 2. The influence of the loading cases on the multiplanar connections have been investigated by analysing each multiplanar connection with five different load ratios, namely J = -1, -0.5, 0, 0.5, 1.

The steel grade used for all RHS column in the numerical modelling is Fe510 with a yield stress of 355 N/mm^2. In order to avoid brace failure before connection failure, a steel grade of StE 690 with a yield stress of 690 N/mm^2 is taken for all I-beams.

Table 1 Summary of the parameters considered for uniplanar and multiplanar I-beam to RHS column connections

Joints		Non-dimensional parameters			
		β	2γ	τ	η
xb1a	xxb1a	0.3	15.8	0.42	0.6
xb2a	xxb2a	0.3	25.0	0.67	0.6
xb3a	xxb3a	0.3	37.5	1.00	0.6
xb4a	xxb4a	0.5	15.8	0.56	1.0
xb5a	xxb5a	0.5	25.0	0.89	1.0
xb6a	xxb6a	0.5	37.5	1.34	1.0
xb7a	xxb7a	0.73	15.8	1.00	2.0
xb8a	xxb8a	0.73	25.0	1.58	2.0
xb9a	xxb9a	0.73	37.5	2.37	2.0
xb10a		0.93	15.8	0.68	0.9
xb11a		0.93	25.0	1.08	0.9
xb12a		0.93	37.5	1.62	0.9
xb14a	xxb14a	0.18	25.0	0.48	0.3
xb15a	xxb15a	0.18	37.5	0.71	0.3

Table 2 The influence of η on axially loaded uniplanar I-beams to RHS column connections (XBAX-E)

	η=0.3	η=0.6	η=1.0	η=1.5	η=2.0	η=2.5
β=0.18		xb14a-e2	xb14a-e3	xb14a-e4	xb14a-e5	xb14a-e6
β=0.50	xb5a-e1	xb5a-e2		xb5a-e4	xb5a-e5	xb5a-e6
β=0.73	xb8a-e1	xb8a-e2	xb8a-e3	xb8a-e4		xb8a-e6
β=0.93	xb11a-e1	xb11a-e2		xb11a-e4	xb11a-e5	xb11a-e6

NUMERICAL MODELLING

The finite element models are generated using the pre- and post processor program SDRC-IDEAS. Eight noded thick shell elements (MARC element type 22) have been used for the connection modelling, which are the same as used for the calibration models with the experiments (Lu, 1993). Because of symmetry in geometry and loading, only an eighth of the connection is modelled in order to reduce the number of elements and nodes. A typical finite element mesh is shown in figure 1 for a multiplanar connection (xxb5a).

It should be mentioned that throughout this parameter study, butt welds are considered which are stronger than the parent material being connected. Since the nominal size of the fillet part of butt welds according to AWS (1992) and Eurocode 3 (1992) is relative small, no weld elements have been modelled in the numerical models. However, the actual weld sizes are general larger than the nominal sizes, this may lead to an increase of the actual connection strength.

During the numerical analyses, displacement control has been used for $N_2/N_1 = 0$ and 1. For $N_2/N_1 = -1$, -0.5 and +0.5, load control is used so that a fixed load ratio applied on the connections can be maintained even after plastic deformation.

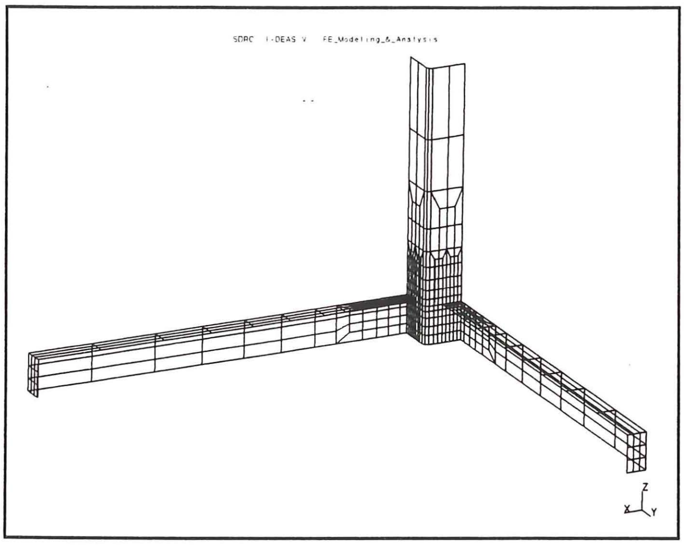

Figure 1 Typical finite element mesh for a multiplanar connection (xxb5a)

OBSERVATIONS OF THE FE ANALYSES

From the post-processing of the numerical modelling, it is found that for the connections with $\beta < 0.93$, the failures of the connections are caused by the chord face yielding, while for connections with $\beta = 0.93$, chord side wall failures occur.

A typical load (N) - displacement (Δ) diagram obtained from the numerical analyses for the uniplanar connections is shown in figure 2, for connections with the same β and η values ($\beta = 0.5$ and $\eta = 1.0$). The influence of 2γ can be directly seen. For the multiplanar connections, a typical load - displacement diagram is given in figure 3, showing the connection behaviour of xxb5a with $\beta = 0.5$, $2\gamma = 25.0$ and $\eta = 1.0$ under five different load ratios.

As no peak loads have been obtained, a deformation limit of $3\%b_0$ at the intersections of I-beam's flanges and chord faces is used in accordance with Lu (1994). The numerically determined strengths at the deformation limit of $3\%b_0$ are summarized in table 3 and table 4 for uniplanar and multiplanar connections separately.

Table 3 The connection strength at a deformation limit of $3\%b_0$ for uniplanar connections

Connections	β	2γ	η	τ	$N_{u,xp} / f_{y0}t_0^2$	$N_{u,xb} / f_{y0} t_0^2$
xb14a	0.18	25.0	0.3	0.48	2.8288	3.8023
xb14a-e2	0.18	25.0	0.6	0.48	2.8288	4.4399
xb14a-e3	0.18	25.0	1.0	0.48	2.8288	5.3565
xb14a-e4	0.18	25.0	1.5	0.48	2.8288	6.5100
xb14a-e5	0.18	25.0	2.0	0.48	2.8288	6.5100
xb5a-e1	0.50	25.0	0.3	0.89	4.4080	5.9543
xb5a-e2	0.50	25.0	0.6	0.89	4.4080	7.0073
xb5a	0.50	25.0	1.0	0.89	4.4080	8.1301
xb5a-e4	0.50	25.0	1.5	0.89	4.4080	9.3983
xb5a-e4-w	0.50	25.0	1.5	0.89	4.4080	8.8488

Table 3 The connection strength at a deformation limit of $3\%b_0$ for uniplanar connections (continued)

xb5a-e5	0.50	25.0	2.0	0.89	4.4080	10.5134
xb5a-e5-w	0.50	25.0	2.0	0.89	4.4080	8.8674
xb5a-e6	0.50	25.0	2.5	0.89	4.4080	11.7185
xb8a-e1	0.73	25.0	0.3	1.58	6.7893	9.6066
xb8a-e2	0.73	25.0	0.6	1.58	6.7893	11.3306
xb8a-e3	0.73	25.0	1.0	1.58	6.7893	12.8527
xb8a	0.73	25.0	2.0	1.58	6.7893	15.1526
xb8a-e6	0.73	25.0	2.5	1.58	6.7893	16.3014
xb11a	0.93	25.0	0.9	1.08	11.4453	22.0037
xb11a-e1	0.93	25.0	0.3	1.08	11.4453	18.1600
xb11a-e2	0.93	25.0	0.6	1.08	11.4453	20.5453
xb11a	0.93	25.0	0.9	1.08	11.4453	22.0037
xb11a-e4	0.93	25.0	1.5	1.08	11.4453	23.6686
xb11a-e5	0.93	25.0	2.0	1.08	11.4453	25.0641
xb11a-e6	0.93	25.0	2.5	1.08	11.4453	26.4737
xb15a	0.18	37.5	0.3	0.71	2.8397	3.7421
xb1a	0.30	15.8	0.6	0.42	3.4184	5.3766
xb2a	0.30	25.0	0.6	0.66	3.3761	5.2168
xb3a	0.30	37.5	0.6	1.00	3.4260	5.0821
xb4a	0.50	15.8	1.0	0.56	4.5465	8.3753
xb6a	0.50	37.5	1.0	1.33	4.5267	8.0048
xb7a	0.73	15.8	2.0	1.00	7.1503	15.9237
xb9a	0.73	37.5	2.0	2.37	7.0482	15.1091
xb10a	0.93	15.8	0.9	0.68	10.5821	19.3814
xb12a	0.93	37.5	0.9	1.62	11.8922	23.4569

Table 4 The connection strength at a deformation limit of $3\%b_0$ for multiplanar connections

					$N_{u,xxb} / f_{y0} t_0^2$				
Name	β	2γ	η	τ	J = 0	J = -0.5	J = -1	J = 0.5	J = 1
xxb14a	0.18	25.0	0.3	0.47	3.8108	2.5880	3.2003	4.0338	4.1678
xxb15a	0.18	37.5	0.3	0.71	3.7680	2.5716	3.1299	4.1575	4.2165
xxb1a	0.30	15.8	0.6	0.42	5.4014	3.4347	4.2918	5.7928	6.3607
xxb2a	0.30	25.0	0.6	0.66	5.2479	3.3585	4.2383	5.5197	5.7308
xxb3a	0.30	37.5	0.6	1.00	5.1770	3.3190	4.1305	5.6201	5.7198
xxb4a	0.50	15.8	1.0	0.56	8.4654	5.3022	6.6612	9.4871	10.7285
xxb5a	0.50	25.0	1.0	0.89	8.2211	5.2165	6.5662	8.6970	9.0965
xxb6a	0.50	37.5	1.0	1.33	8.2166	5.2357	6.5150	8.8079	8.9723
xxb7a	0.73	15.8	2.0	1.00	16.3870	10.3290	12.9834	19.3100	22.6163
xxb8a	0.73	25.0	2.0	1.58	15.3106	9.6938	12.1409	16.8441	17.7192
xxb9a	0.73	37.5	2.0	2.37	15.3685	9.9021	12.3217	16.9359	16.1810

The non-dimensional strengths of connections at the deformation limit for uniplanar connections have been compared with the strengths of the connections between plates and RHS columns with the same β, 2γ and τ values (Lu, 1995). The ratios of the strengths have been plotted against η in figure 4 so that the influence of the second flange and web of an I-beam on the strengths of the connections is demonstrated. As can be seen, the strengths of the connections with the same β, 2γ and τ values increase almost linearly with the increase of the η values. The increase is stronger for connections with small β values.

It should be mentioned that the strengths of the connections with $\eta > 1.5$ are higher then twice the strength of the connection between plates and RHS columns because of the webs of the I-beams. Two extra calculations have been carried out on connections xb5a-e4 and xb5a-e5 with $\beta = 0.5$ without webs between two flanges. The results are shown in figure 4 with solid symbols. As can be expected, the strengths become twice the strength of plate to RHS connection.

Further, the strengths of the multiplanar connections with J = 0 have been compared with the strength of the corresponding uniplanar connections. As shown in figure 5, almost no difference is found between the strength of the multiplanar connections with J = 0 and the strength of the corresponding uniplanar connections. Finally, the multiplanar loading effects are shown in figure 6. A positive load ratio (J = 0.5 and J = 1) causes generally an increase of the strength compared to that of the connections with J = 0, while a negative load ratio (J = -0.5 and J = -1) leads to a significant reduction in the strength of the connection.

STRENGTH OF THE UNIPLANAR CONNECTIONS

Since in the numerical modelling, cracks can not yet be modelled, punching shear failure can not be checked numerically. Only chord face yielding and chord side wall failures are observed. For chord face yielding, analytical strength formulae can be developed based on the yield line model. These have been made for various connections and loading.
For uniplanar plate to RHS column connections, this results in the following formula (Lu, 1995):

$$\frac{N_{u,xp}}{f_{y0}t_0^2} = \frac{4}{\sqrt{1-\beta}} \qquad (1)$$

For axially loaded uniplanar I-beam to RHS column connections, following equation applies:

$$\frac{N_{u,xb}}{f_{y0}t_0^2} = \frac{4}{\sqrt{1-\beta}} + \frac{2\eta}{1-\beta} \qquad (2)$$

In formulae (1) and (2) the geometrical influence of the I-beam flange thickness and the geometrical influence of the RHS column thickness have been neglected.

The numerically determined connection strengths based on a deformation limit of $3\%b_0$, however, do not fit the analytically determined functions (1) and (2) correctly, especially for small β ratios. As already shown in (Lu, 1995), the numerically determined strengths $N_{u,xp}$ for plate to RHS column connections at the deformation limit of $3\%b_0$ are about 45% lower then the analytical strengths for $\beta = 0.18$. This is because the analytical strength can be only obtained after large deformations when the chord face yield lines have developed. For large β values, e.g. for $\beta = 0.73$ however, the numerically determined strengths at the deformation of $3\%b_0$ approach the analytical strengths. Using equation (1) as basis, following equation has been determined with a regression analysis for uniplanar plate to RHS column connections (Lu, 1995) :
Chord face yielding :

$$\frac{N_{u,xp}}{f_{y0}t_0^2} = (0.5 + 0.7\beta) * \frac{4}{\sqrt{1-0.9\beta}} \qquad (3)$$

For chord side wall failure, the criterion given by CIDECT design guide (1992) has been used as a limitation for high β values :

$$N_{u,xp} = 2(t_1 + 5t_0)\, f_{y0}t_0 \qquad (4)$$

In order to get the effect of the second flange and web of an I-beam on the connection behaviour, in this paper, the numerically determined strength $N_{u,xb}$ has been compared with the numerically determined strength $N_{u,xp}$ for plate to RHS column connections with the same β, 2γ and τ values. The ratios of $N_{u,xb}$ and $N_{u,xp}$ have been plotted against η in figure 4 so that the influence of η can be seen directly.

Figure 4 shows that for $\eta \geq 0.5$ the strength of the connection increases nearly linear with increasing η values. With respect to β, however, two stages are observed. For $\eta < 0.5$, the increase is stronger for large β values, which is in accordance with the analytical model given by the ratio of equation (2) and (1) :

$$\frac{N_{u,xb}}{N_{u,xp}} = 1 + \frac{\eta}{2\sqrt{1-\beta}} \qquad (5)$$

For $\eta > 0.5$, however, the β influence is in contradiction to the analytical equation (5). It means that for small β values the effect of η is stronger. This can be easily explained since the analytical strength is obtained after large displacement, while the numerically determined strength at a deformation limit of $3\%b_0$ is much lower for small β values. As a consequence an opposite influence of parameter β is obtained compared to the analytical equation (5).

To determine a representative effect of the second flange and web of an I-beam on the strength for compression loaded uniplanar I-beam to RHS column connections, regression analyses have been carried out for $\eta > 0.5$. This effect is described by equation (6), which is based on the numerical results and the analytical model. The statistical results of the regression analysis are listed in table 5.

$$f(\beta, \eta) = \left(\frac{1}{1.12\,(1-0.9\beta)} + \frac{\eta}{(0.8+2.4\beta)\sqrt{(1-0.9\beta)}} \right) \{1-(0.9\beta)^2\} \quad \text{for} \quad \eta \geq 0.5 \qquad (6)$$

Table 5 Results of regression analyses for uniplanar I-beam to RHS connections

No. of data points	30
Mean norm. errors	1.002
Correlation coefficient r^2	0.996
Coefficient of var. COV	0.025

For $\eta < 0.5$, the effect can be described by a linear function between 1.0 and the value for η = 0.5.

$$f(\beta, \eta) = 1 + \frac{\eta}{0.5}\,\{ f(\beta, \eta=0.5) - 1 \} \quad \text{for } \eta < 0.5 \qquad (7)$$

The strength for a compression loaded uniplanar I-beam to RHS column connection $N_{u,xb}$ is obtained by multiplying the strength of plate to RHS column connections $N_{u,xp}$ (see equation (3) by the function $f(\beta, \eta)$ according to (6) and (7) :

$$N_{u,xb} = f(\beta, \eta)\, N_{u,xp} \qquad (8)$$

The strength is limited by the criterion chord side failure, in accordance with the criterion given by CIDECT design guide (1992) :

$$N_{u,xb} = 4\,(t_1+5t_0)\, f_{y0} t_0 \quad \text{for } h_1 \geq 2t_1+5t_0 \qquad (9)$$

$$N_{u,xb} = 2\,(h_1+5t_0)\, f_{y0} t_0 \quad \text{for } h_1 < 2t_1+5t_0 \qquad (10)$$

MULTIPLANAR LOAD EFFECT

As shown in figure 5, almost no difference in strength is found between uniplanar and multiplanar connections with J = 0. Therefore, formula (6) to (10) can be used as the strength formula for multiplanar connections with J = 0.

The influence of the multiplanar loading on two sets of I-beams is shown in figure 6. On the vertical axis, the strength ratio between connections loaded with J≠0 and connections loaded with J=0 is given. It can be seen that when the connections are loaded with positive load ratios, the connection strengths increase. The increase of the connection strength for a positive load ratio is more pronounced for connections with a small 2γ value and a higher β value. In this case, the load transfer is more directly by axial stresses in the corners. For other cases however, the increase of the connection strength is less than 20%. Therefore, it is proposed to use the strength according to equation (6) to (9) for $J = 0$ as a conservative lower bound for connections with $J > 0$.

For negative load ratios however, the connection strength decreases significantly, linear with J. This multiplanar loading influence is described by equation (11) :

$$f(J) = 1 + 0.37J \qquad J < 0 \tag{11}$$

The regression results of this formula are given in table 6.

Table 6 Results of regression analyses for negative multiplanar loading influence

No. of data points	33
Mean norm. errors	1.003
Correlation coefficient r^2	0.999
Coefficient of var. COV	0.025

The strengths for multiplanar connections between I-beams and RHS columns is obtained:

$$N_{u,xxb} = f(J)\, N_{u,xb} \quad \begin{cases} f(J) = 1 & \text{for } J \geq 0 \\ f(J) = 1 + 0.37J & \text{for } J < 0 \end{cases} \tag{12}$$

The strength formulae for axially loaded I-beam to RHS column connection are summarized in table 7.

CONCLUSIONS

Based on the results of the previous and present research, the following conclusions can be drawn :

- The strength of compression loaded uniplanar I-beam to RHS column connection can be given by multiplying the strength for plate to RHS column connection by a function $f(\beta, \eta)$, as given in table 7.
- The strength of multiplanar connections with $J = 0$ is not influenced by the non-loaded out-of plane I-beams if compared to the strength of the corresponding uniplanar connections. A positive load ratio causes an increase of the strength of the multiplanar connections, but this effect has been neglected. The same formulae as used for butt welded uniplanar connections can therefore be used for multiplanar I-beam to RHS column connections with $J \geq 0$.
- The strength of multiplanar connections is reduced significantly by negative load ratios ($J < 0$). This effect is described by equation(11).

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Table 7 Strength formulae for axially loaded I-beam to RHS column connections

Uniplanar Connection	$N_{u,xb} = f(\beta,\eta)\ N_{u,xp}$
	Chord face yielding : $\frac{N_{u,xp}}{f_{y0}t_0^2} = (0.5 + 0.7\beta) * \frac{4}{\sqrt{1-0.9\beta}}$ $f(\beta, \eta) = 1 + \frac{\eta}{0.5}\ \{ f(\beta, \eta{=}0.5) - 1 \}$ for $\eta < 0.5$ $f(\beta, \eta) = \frac{1.25}{(1-0.9\beta)} + \frac{\eta}{(0.8+2.4\beta)\sqrt{(1-0.9\beta)}})\ \{1 - (0.9\beta)^2\}$ for $\eta \geq 0.5$
	Chord side failure : $N_{u,xp} = 2(t_1 + 5t_0)\ f_{y0}t_0$ $N_{u,xb} = 4\ (t_1 + 5t_0)\ f_{y0}t_0$ for $h_1 \geq 2t_1 + 5t_0$ $N_{u,xb} = 2\ (h_1 + 5t_0)\ f_{y0}t_0$ for $h_1 < 2t_1 + 5t_0$
Multiplanar Connection	$N_{u,xxb} = f(J)\ N_{u,xb}$ $f(J) = 1$ $J \geq 0$ $f(J) = 1 + 0.37J$ $J < 0$

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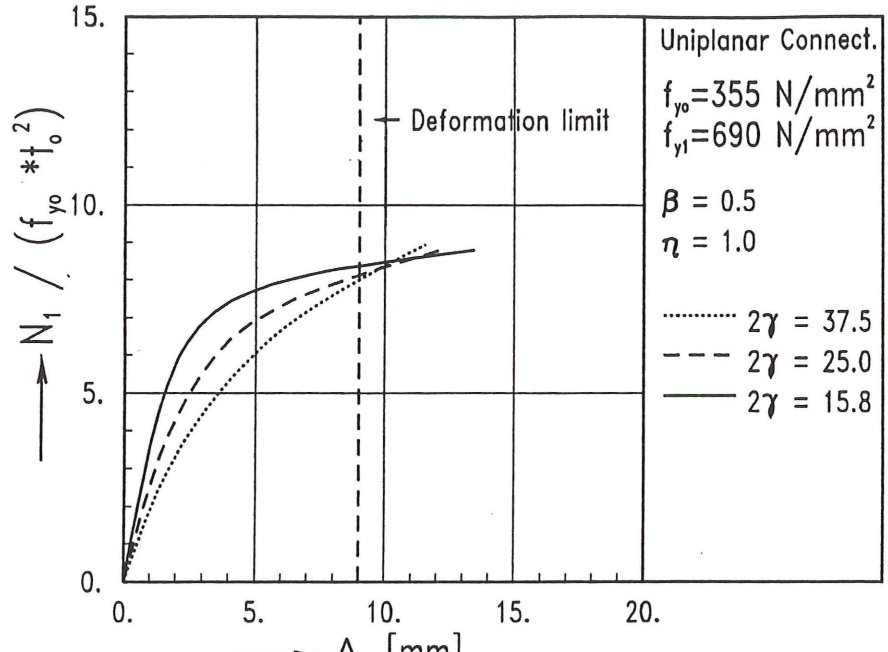

Fig. 2 Load – displacement curves for β = 0.50

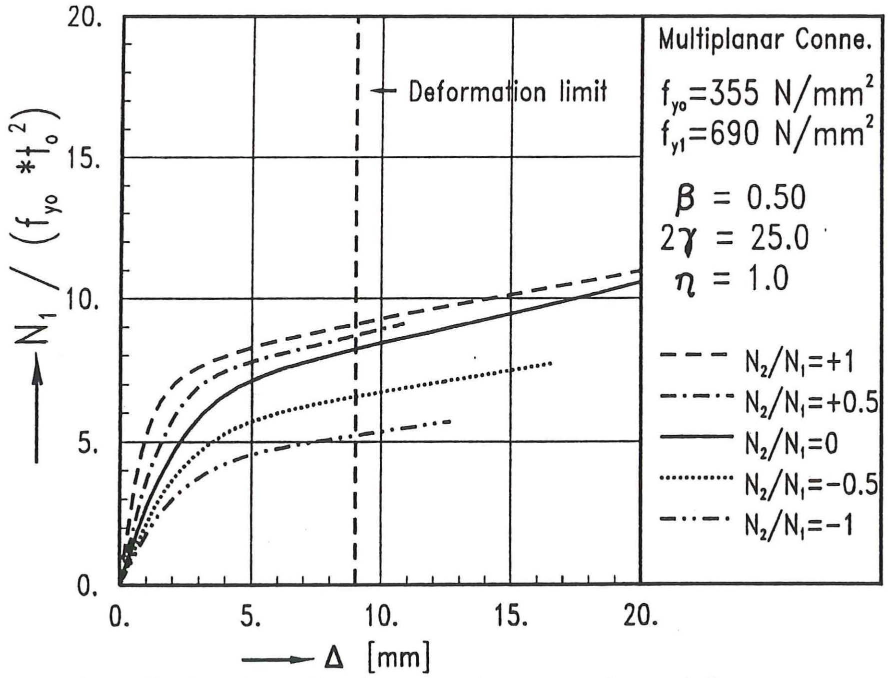

Fig. 3 Load – displacement curves for xxb5a

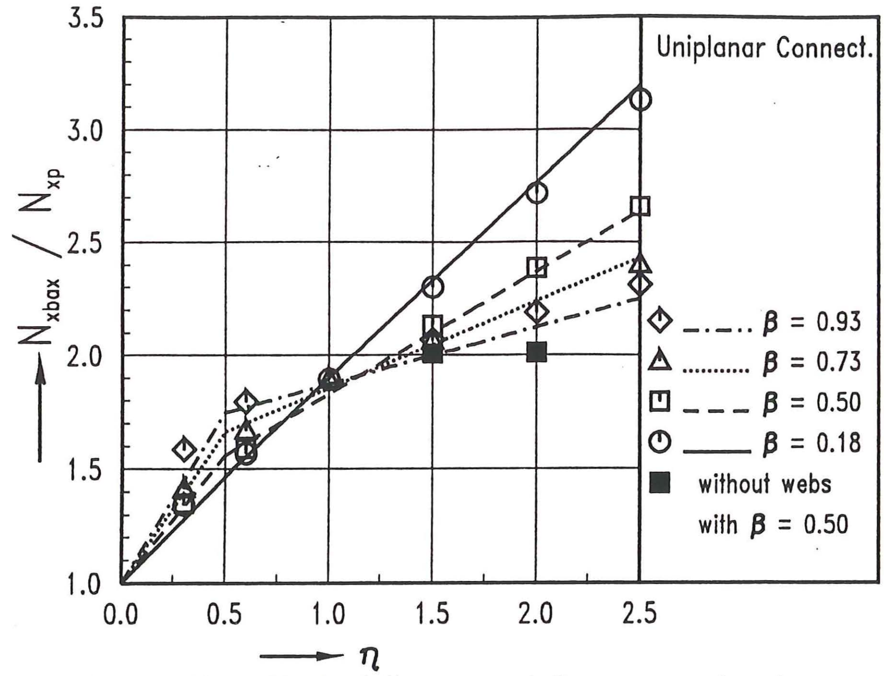

Fig. 4 The effect of the second flange and web

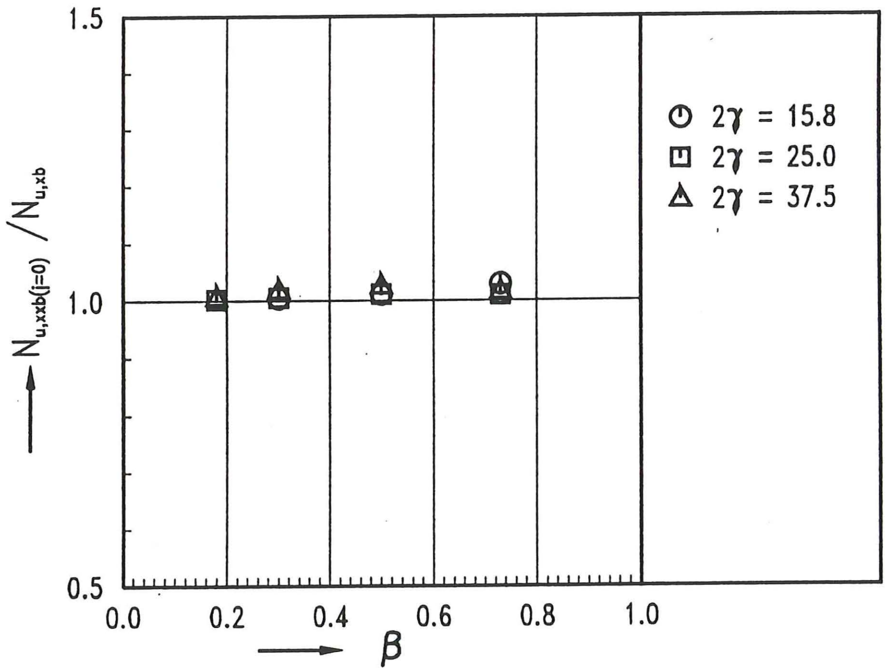

Fig. 5 Comparisons between multiplanar connections with J=0 and corresponding uniplanar connections

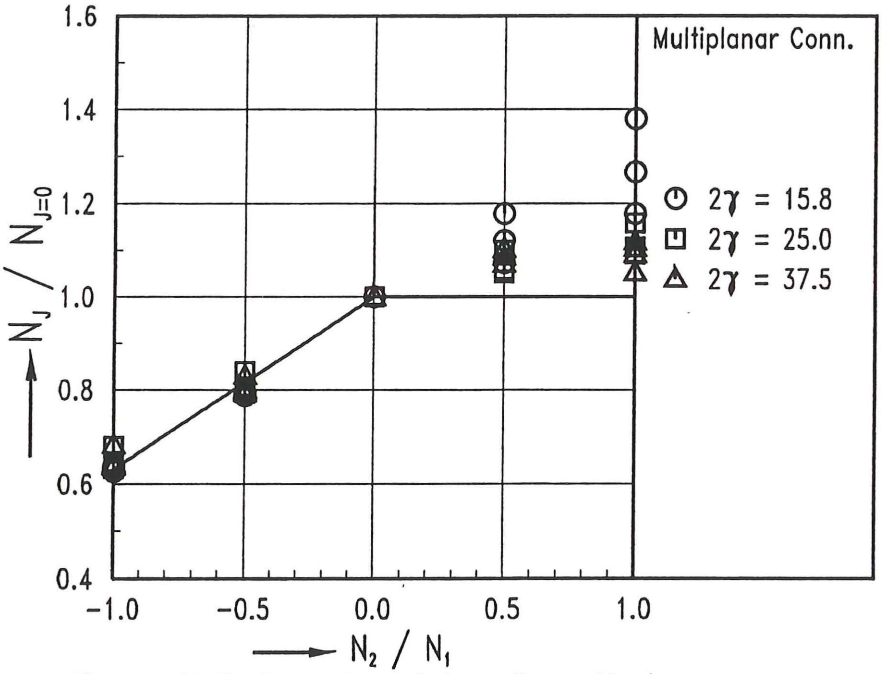

Fig. 6 Multiplanar load interaction effect