CHAPTER FOUR
RESULTS, DISCUSSION AND COMPARISON

4.1 General

In this chapter, the analysis results of 192 finite element models (96-web crippling models and 96-bending and web crippling models) carried out on cold formed steel channels subjected to web crippling under (IOF) loading case were presented. The influence of cross section parameters on web crippling strength was discussed. The finite element strengths were compared with the design strengths predicted by AS/NZS, BS-5950, ECP and NAS specifications. The comparisons included both web crippling and interaction of bending and web crippling models. New web crippling coefficients were calibrated and proposed for the ECP and NAS unified web crippling design equation. Also, modified interaction equation was suggested for both codes.

4.2 Analysis Results of Web Crippling Models

The modeled channel dimensions and their ultimate web crippling strengths "P_{FE}" predicted by the nonlinear finite element analysis are presented in Table 4.1 through 4.8. The modeled channels were labeled such that the series number, the cross section type, the total web depth, the total flange width, the cross section thickness, the inside bend radius, the bearing load length and the material yield strength could be identified. For example, specimen label "S7-C100×50×2-R9-N50-F360" defines the following:

1. The first two characters indicate that the specimen belongs to a series "S7".
2. The next four characters indicate that a Channel cross section of total web depth, D = 100 mm.
3. The next two numbers indicate that the channel flange width, b = 50 mm.
4. The next number indicates that the channel thickness, t = 2 mm.
5. The next two characters indicate that the inside bend radius, R = 9 mm.
6. The next three characters indicate that the length of bearing load, N = 50 mm.
7. The last four characters indicate that the material yield stress, F_y = 360 N/mm^2.

Figures 4.1 through 4.8 show samples of von misses stress distributions and deformed shapes for different web crippling models at the ultimate load. It was observed that, in most models yielding first occurs at the top web- flange intersection along the bearing load length.

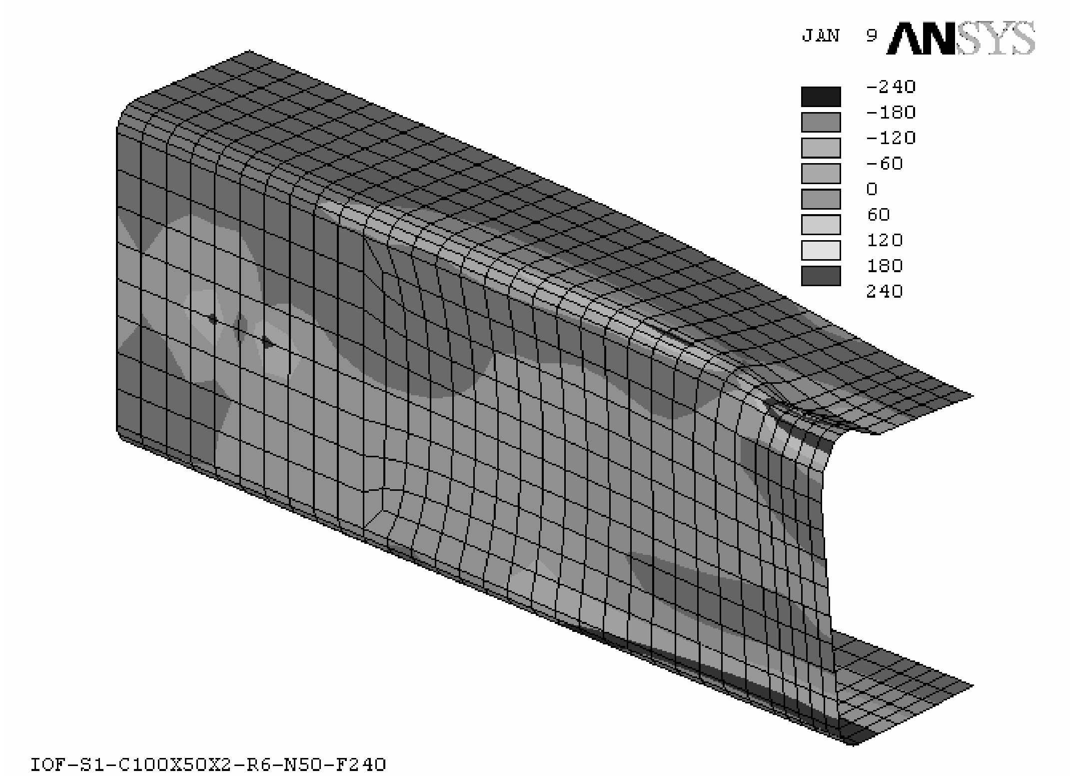

Fig. 4.1 Von Misses stresses of model "S1-C100×50×2-R6-N50-F240"

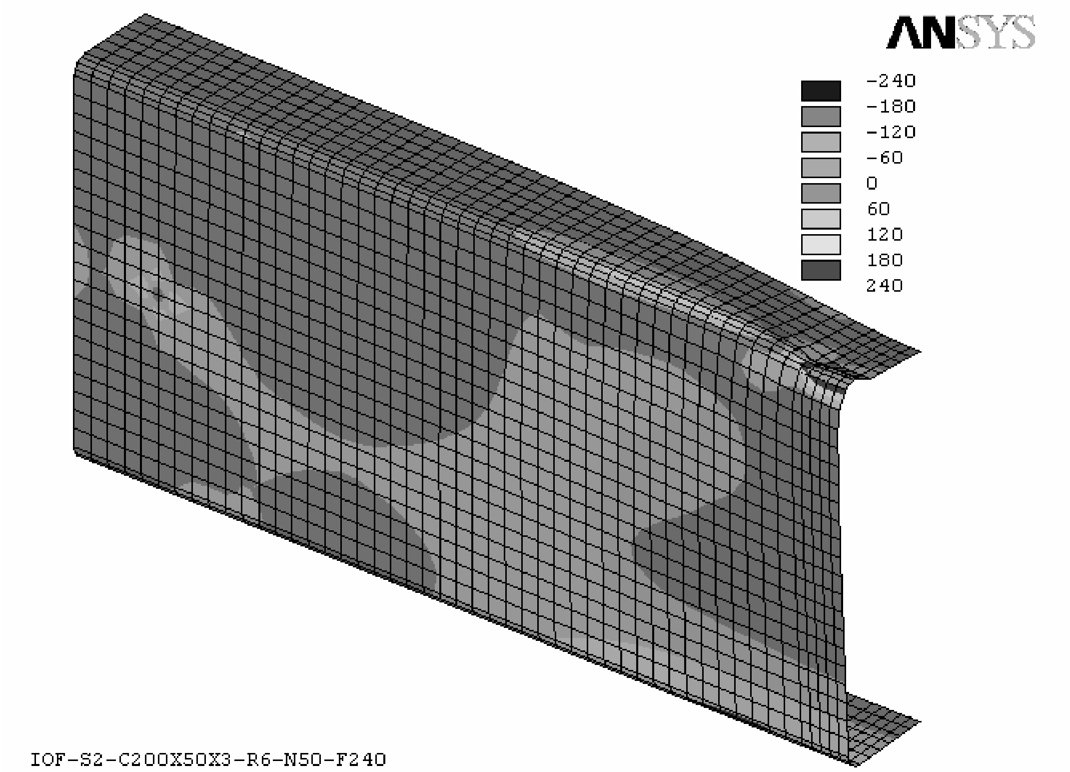

Fig. 4.2 Von Misses stresses of model "S2-C200×50×3-R6-N50-F240"

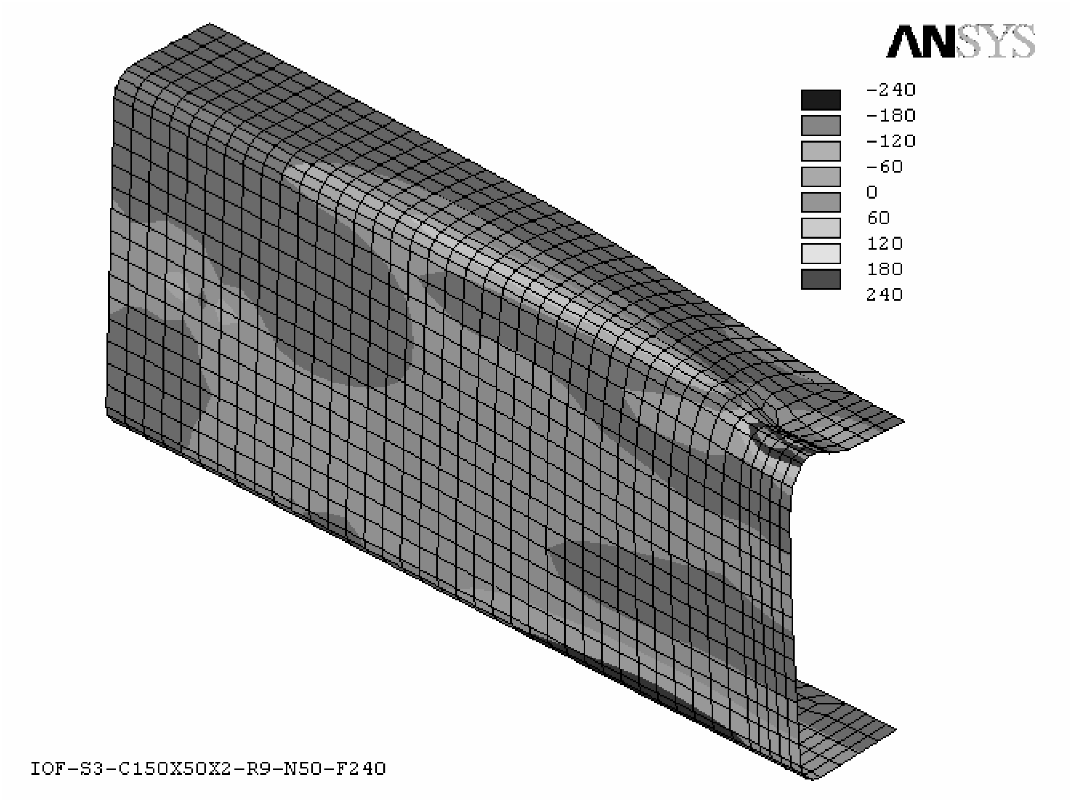

Fig. 4.3 Von Misses stresses of model "S3-C150×50×2-R9-N50-F240"

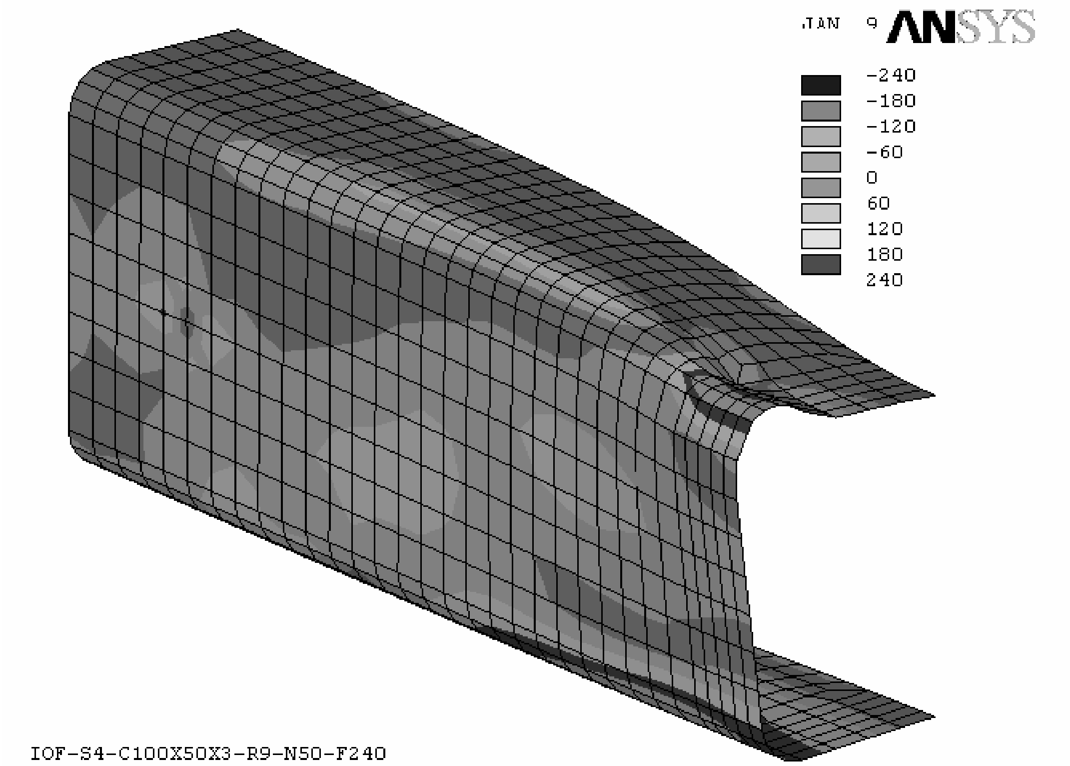

Fig. 4.4 Von Misses stresses of model "S4-C100×50×3-R9-N50-F240"

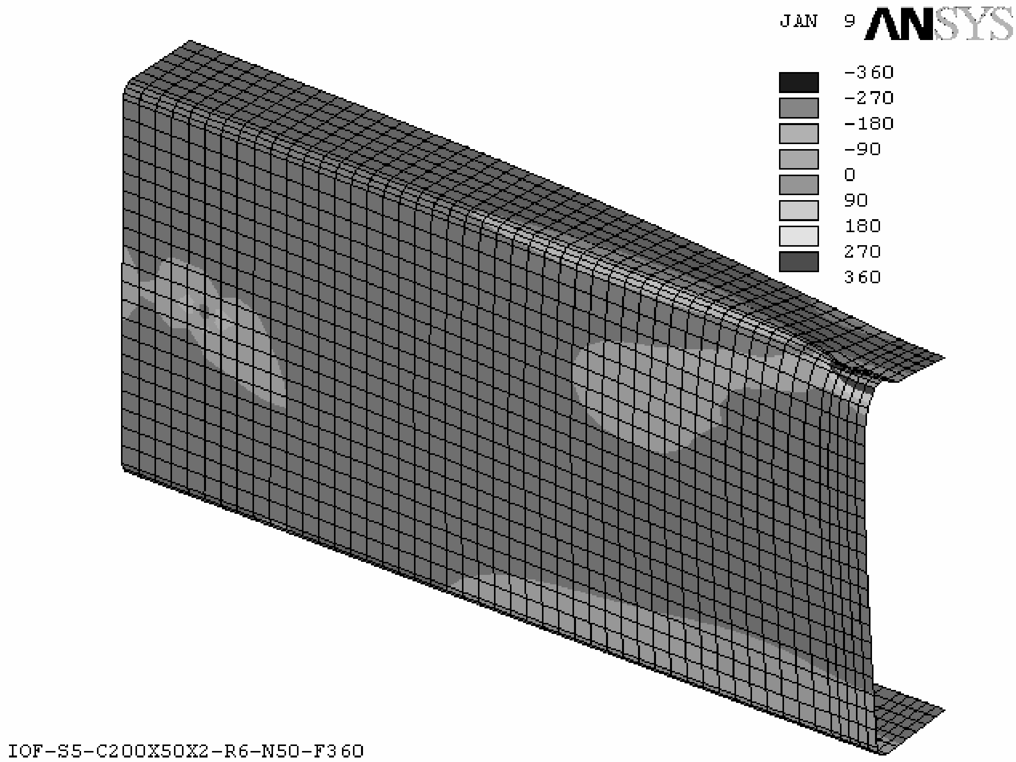

Fig. 4.5 Von Misses stresses of model "S5-C200×50×2-R6-N50-F360"

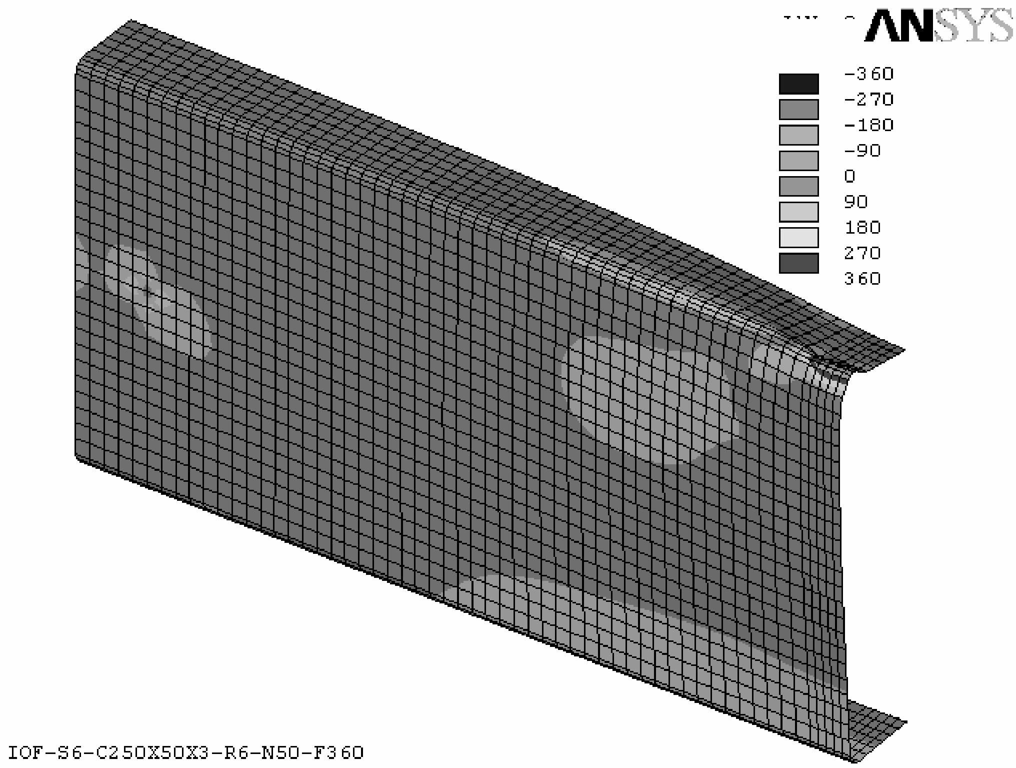

Fig. 4.6 Von Misses stresses of model " S6-C250×50×3-R6-N50-F360"

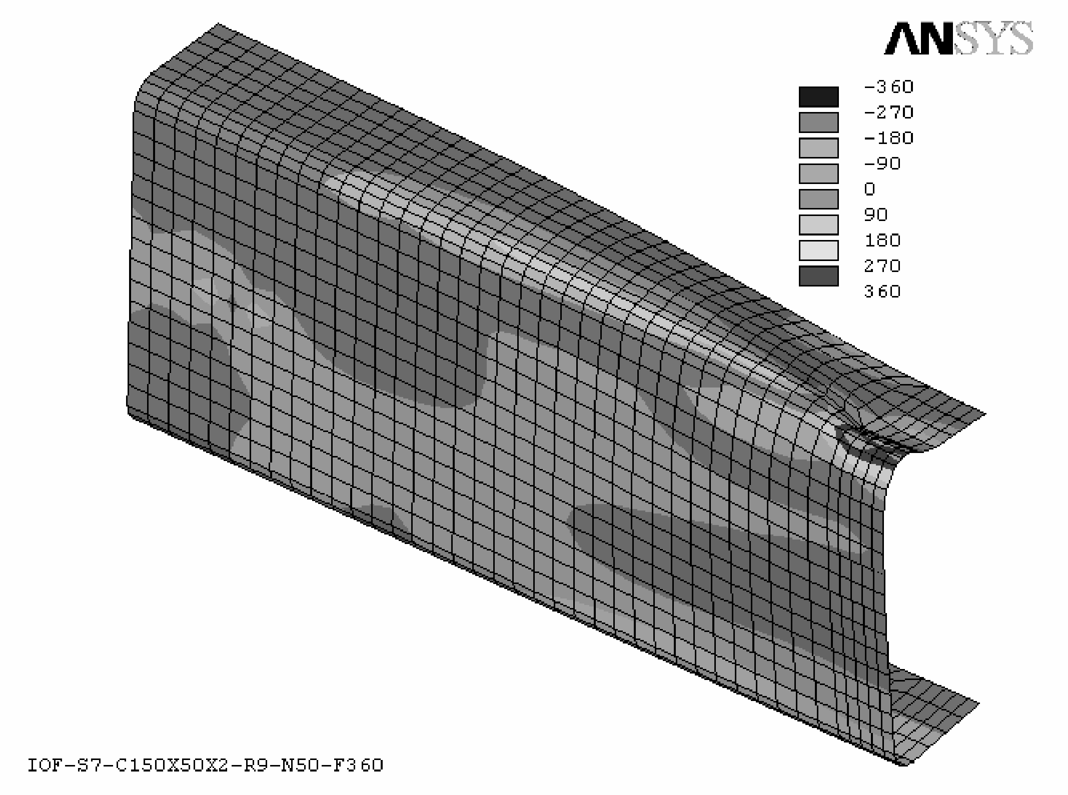

Fig. 4.7 Von Misses stresses of model "S7-C150×50×2-R9-N50-F360"

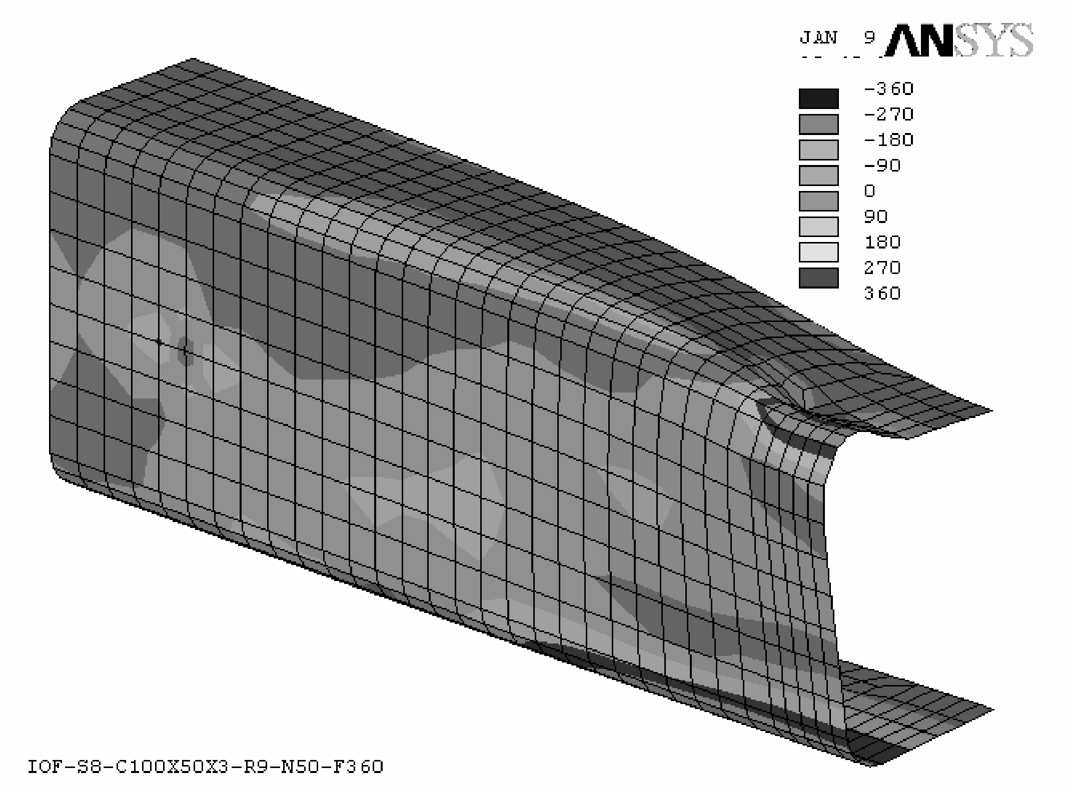

Fig. 4.8 Von Misses stresses of model "S8-C100×50×3-R9-N50-F360"

Figures 4.9 through 4.16 show samples of load versus web deformation curves for different web crippling models. In most models it was observed that, after the ultimate load an increase in the load capacity occurs due to strain hardening as shown below.

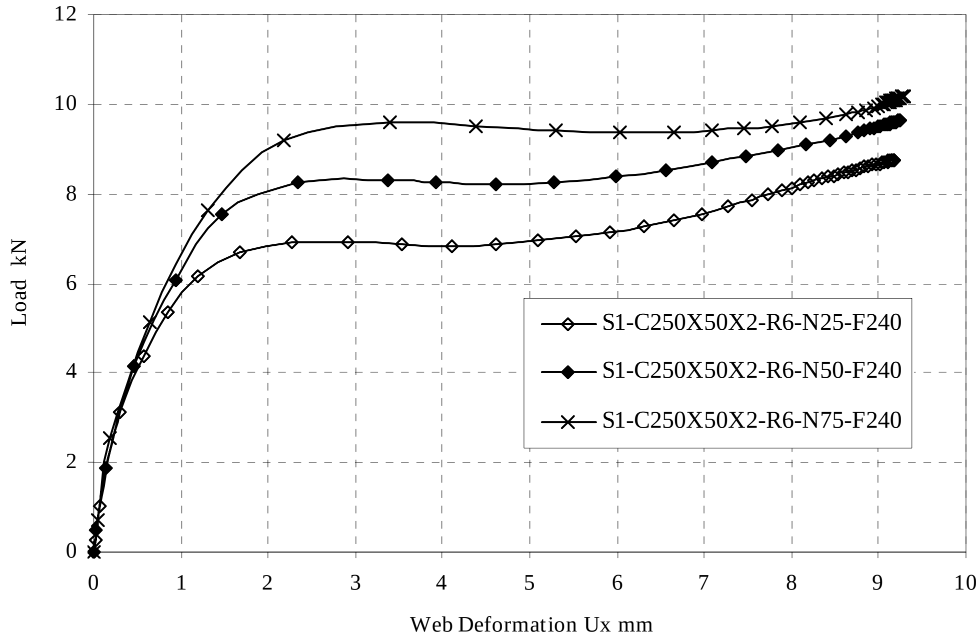

Fig. 4.9 Load versus web deformations for models "S1-C250×50×2-R6-F240"

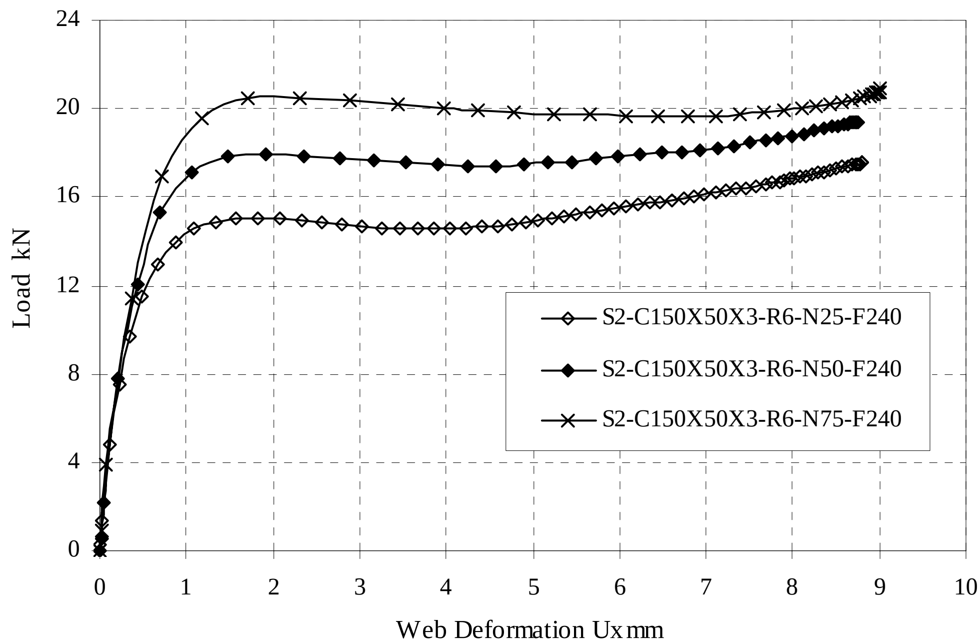

Fig. 4.10 Load versus web deformations for model "S2-C150×50×3-R6-F240"

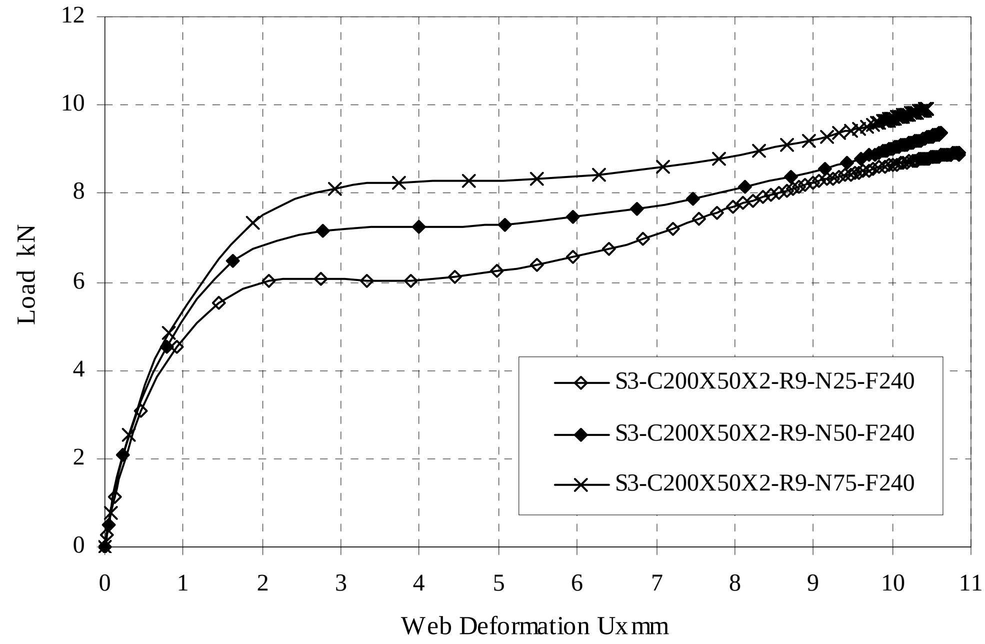

Fig. 4.11 Load versus web deformations for model "S3-C200×50×2-R9-F240"

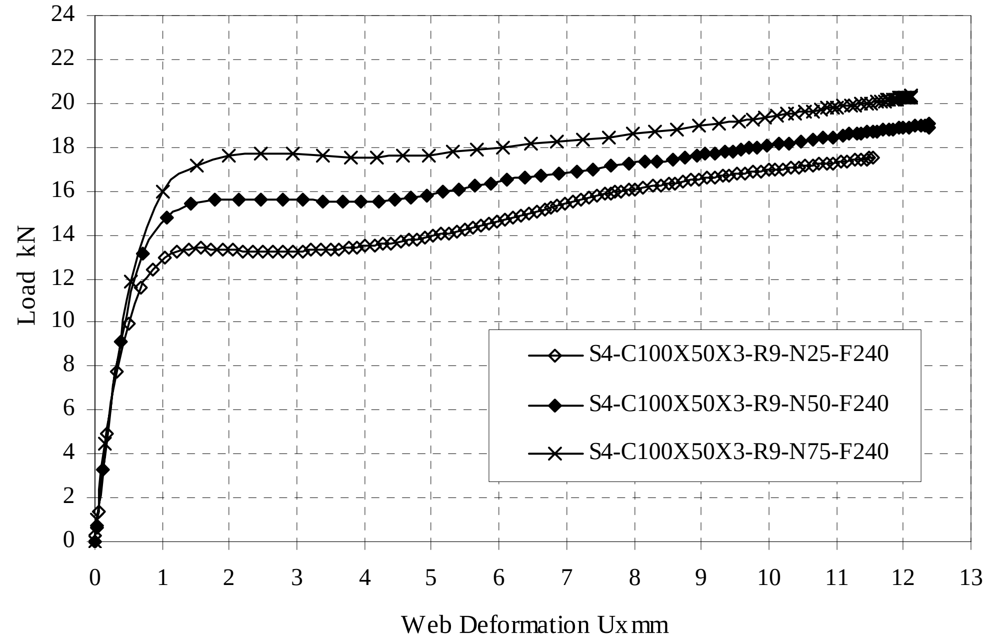

Fig. 4.12 Load versus web deformations for model "S4-C100×50×3-R9-F240"

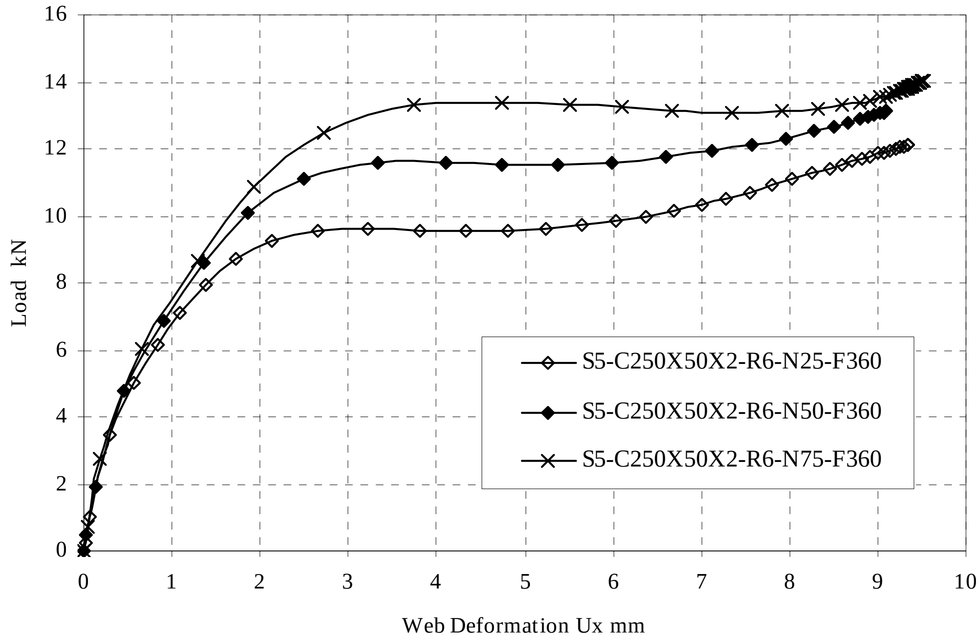

Fig. 4.13 Load versus web deformations for model "S5-C250×50×2-R6-F360"

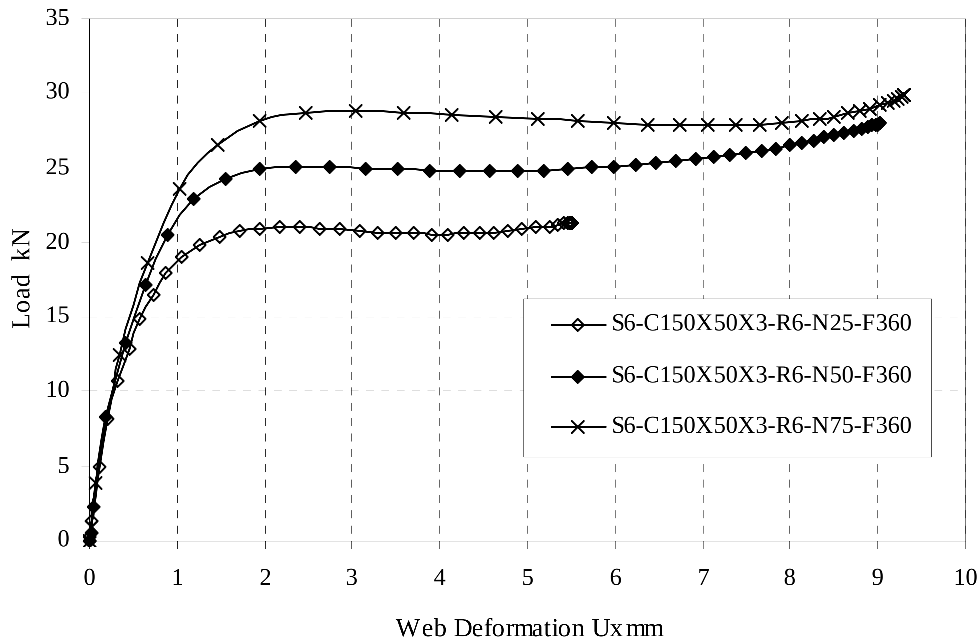

Fig. 4.14 Load versus web deformations versus for model "S6-C150×50×3-R6-F360"

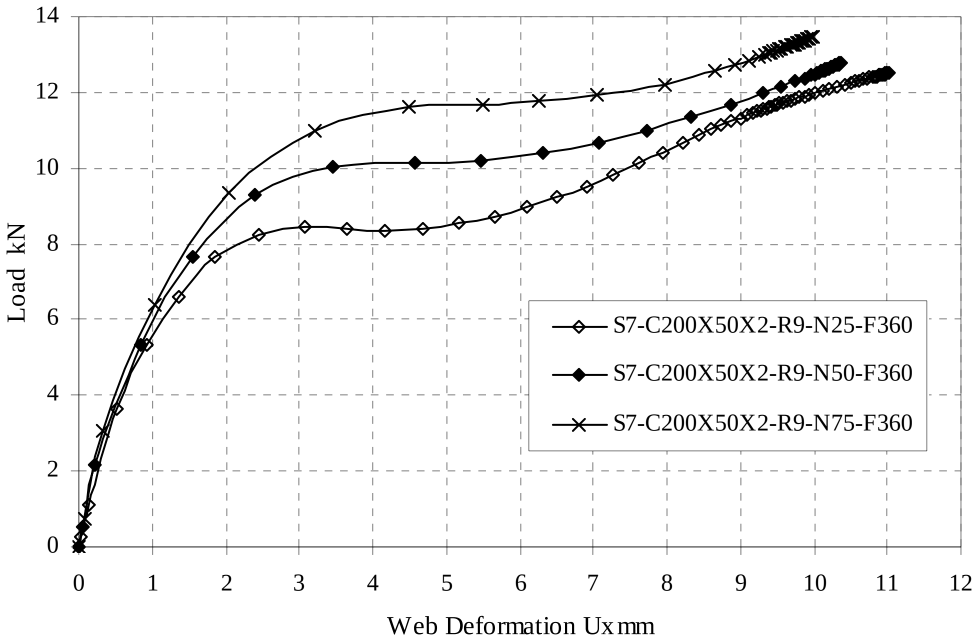

Fig. 4.15 Load versus web deformations for model "S7-C200×50×2-R9-F360"

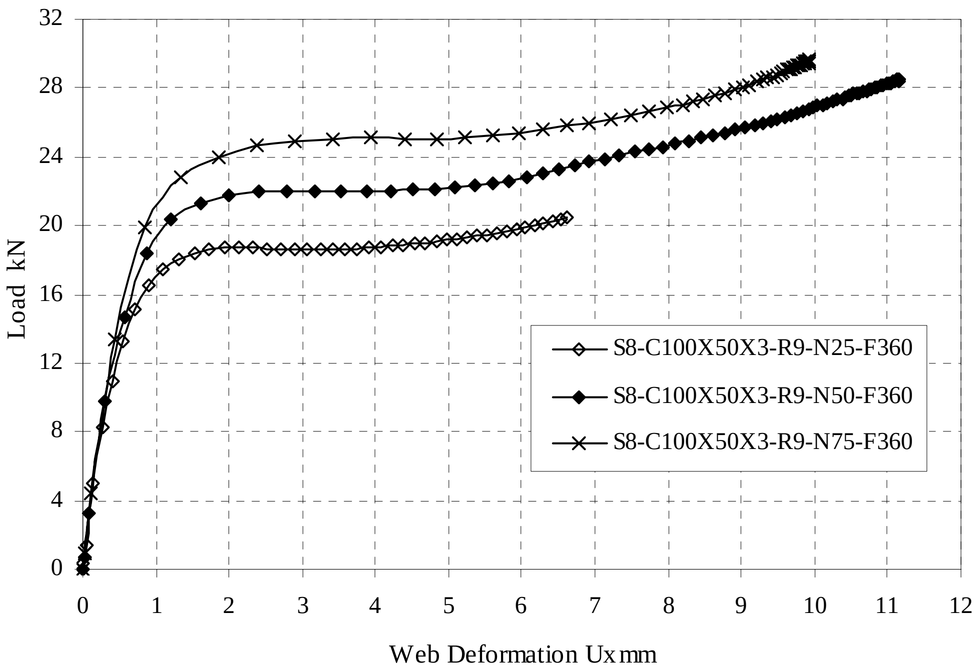

Fig. 4.16 Load versus web deformations for model "S8-C100×50×3-R9-F360"

Table 4.1 Specimen dimensions and finite element web crippling strength P_{FE} for Series S1

Specimen Label	Web D mm	Flanges b mm	Thickness t mm	Radius R mm	Bearing N mm	Length L mm	P_{FE} kN
S1-C100×50×2-R6-N25-F240	100	50	2	6	25	415	8.35
S1-C100×50×2-R6-N50-F240	100	50	2	6	50	440	9.23
S1-C100×50×2-R6-N75-F240	100	50	2	6	75	465	9.95
S1-C150×50×2-R6-N25-F240	150	50	2	6	25	565	8.32
S1-C150×50×2-R6-N50-F240	150	50	2	6	50	590	9.19
S1-C150×50×2-R6-N75-F240	150	50	2	6	75	615	9.94
S1-C200×50×2-R6-N25-F240	200	50	2	6	25	715	8.23
S1-C200×50×2-R6-N50-F240	200	50	2	6	50	740	9.06
S1-C200×50×2-R6-N75-F240	200	50	2	6	75	765	9.71
S1-C250×50×2-R6-N25-F240	250	50	2	6	25	865	8.22
S1-C250×50×2-R6-N50-F240	250	50	2	6	50	890	9.02
S1-C250×50×2-R6-N75-F240	250	50	2	6	75	915	9.67

Table 4.2 Specimen dimensions and finite element web crippling strength P_{FE} for Series S2

Specimen Label	Web d mm	Flanges b mm	Thickness t mm	Radius R mm	Bearing N mm	Length L mm	P_{FE} kN
S2-C100×50×3-R6-N25-F240	100	50	3	6	25	415	16.35
S2-C100×50×3-R6-N50-F240	100	50	3	6	50	440	18.14
S2-C100×50×3-R6-N75-F240	100	50	3	6	75	465	19.59
S2-C150×50×3-R6-N25-F240	150	50	3	6	25	565	16.35
S2-C150×50×3-R6-N50-F240	150	50	3	6	50	590	18.14
S2-C150×50×3-R6-N75-F240	150	50	3	6	75	615	19.55
S2-C200×50×3-R6-N25-F240	200	50	3	6	25	715	16.29
S2-C200×50×3-R6-N50-F240	200	50	3	6	50	740	18.12
S2-C200×50×3-R6-N75-F240	200	50	3	6	75	765	19.44
S2-C250×50×3-R6-N25-F240	250	50	3	6	25	865	16.29
S2-C250×50×3-R6-N50-F240	250	50	3	6	50	890	18.11
S2-C250×50×3-R6-N75-F240	250	50	3	6	75	915	19.36

Table 4.3 Specimen dimensions and finite element web crippling strength P_{FE} for Series S3

Specimen Label	Web d mm	Flanges b mm	Thickness t mm	Radius R mm	Bearing N mm	Length L mm	P_{FE} kN
S3-C100×50×2-R9-N25-F240	100	50	2	9	25	415	8.21
S3-C100×50×2-R9-N50-F240	100	50	2	9	50	440	9.07
S3-C100×50×2-R9-N75-F240	100	50	2	9	75	465	9.71
S3-C150×50×2-R9-N25-F240	150	50	2	9	25	565	8.11
S3-C150×50×2-R9-N50-F240	150	50	2	9	50	590	8.94
S3-C150×50×2-R9-N75-F240	150	50	2	9	75	615	9.57
S3-C200×50×2-R9-N25-F240	200	50	2	9	25	715	8.02
S3-C200×50×2-R9-N50-F240	200	50	2	9	50	740	8.86
S3-C200×50×2-R9-N75-F240	200	50	2	9	75	765	9.48
S3-C250×50×2-R9-N25-F240	250	50	2	9	25	865	7.90
S3-C250×50×2-R9-N50-F240	250	50	2	9	50	890	8.69
S3-C250×50×2-R9-N75-F240	250	50	2	9	75	915	9.21

Table 4.4 Specimen dimensions and finite element web crippling strength P_{FE} for Series S4

Specimen Label	Web d mm	Flanges b mm	Thickness t mm	Radius R mm	Bearing N mm	Length L mm	P_{FE} kN
S4-C100×50×3-R9-N25-F240	100	50	3	9	25	415	16.03
S4-C100×50×3-R9-N50-F240	100	50	3	9	50	440	17.91
S4-C100×50×3-R9-N75-F240	100	50	3	9	75	465	19.32
S4-C150×50×3-R9-N25-F240	150	50	3	9	25	565	15.83
S4-C150×50×3-R9-N50-F240	150	50	3	9	50	590	17.68
S4-C150×50×3-R9-N75-F240	150	50	3	9	75	615	19.24
S4-C200×50×3-R9-N25-F240	200	50	3	9	25	715	15.74
S4-C200×50×3-R9-N50-F240	200	50	3	9	50	740	17.62
S4-C200×50×3-R9-N75-F240	200	50	3	9	75	765	18.97
S4-C250×50×3-R9-N25-F240	250	50	3	9	25	865	15.71
S4-C250×50×3-R9-N50-F240	250	50	3	9	50	890	17.55
S4-C250×50×3-R9-N75-F240	250	50	3	9	75	915	18.90

Table 4.5 Specimen dimensions and finite element web crippling strength P_{FE} for Series S5

Specimen Label	Web d mm	Flanges b mm	Thickness t mm	Radius R mm	Bearing N mm	Length L mm	P_{FE} kN
S5-C100×50×2-R6-N25-F360	100	50	2	6	25	415	11.94
S5-C100×50×2-R6-N50-F360	100	50	2	6	50	440	13.23
S5-C100×50×2-R6-N75-F360	100	50	2	6	75	465	14.32
S5-C150×50×2-R6-N25-F360	150	50	2	6	25	565	11.78
S5-C150×50×2-R6-N50-F360	150	50	2	6	50	590	13.06
S5-C150×50×2-R6-N75-F360	150	50	2	6	75	615	14.01
S5-C200×50×2-R6-N25-F360	200	50	2	6	25	715	11.54
S5-C200×50×2-R6-N50-F360	200	50	2	6	50	740	12.60
S5-C200×50×2-R6-N75-F360	200	50	2	6	75	765	13.57
S5-C250×50×2-R6-N25-F360	250	50	2	6	25	865	11.48
S5-C250×50×2-R6-N50-F360	250	50	2	6	50	890	12.51
S5-C250×50×2-R6-N75-F360	250	50	2	6	75	915	13.38

Table 4.6 Specimen dimensions and finite element web crippling strength P_{FE} for Series S6

Specimen Label	Web d mm	Flanges b mm	Thickness t mm	Radius R mm	Bearing N mm	Length L mm	P_{FE} kN
S6-C100×50×3-R6-N25-F360	100	50	3	6	25	415	21.34
S6-C100×50×3-R6-N50-F360	100	50	3	6	50	440	25.17
S6-C100×50×3-R6-N75-F360	100	50	3	6	75	465	28.92
S6-C150×50×3-R6-N25-F360	150	50	3	6	25	565	21.33
S6-C150×50×3-R6-N50-F360	150	50	3	6	50	590	25.12
S6-C150×50×3-R6-N75-F360	150	50	3	6	75	615	28.76
S6-C200×50×3-R6-N25-F360	200	50	3	6	25	715	21.18
S6-C200×50×3-R6-N50-F360	200	50	3	6	50	740	24.96
S6-C200×50×3-R6-N75-F360	200	50	3	6	75	765	28.45
S6-C250×50×3-R6-N25-F360	250	50	3	6	25	865	21.16
S6-C250×50×3-R6-N50-F360	250	50	3	6	50	890	24.92
S6-C250×50×3-R6-N75-F360	250	50	3	6	75	915	28.38

Table 4.7 Specimen dimensions and finite element web crippling strength P_{FE} for Series S7

Specimen Label	Web d mm	Flanges b mm	Thickness t mm	Radius R mm	Bearing N mm	Length L mm	P_{FE} kN
S7-C100×50×2-R9-N25-F360	100	50	2	9	25	415	11.66
S7-C100×50×2-R9-N50-F360	100	50	2	9	50	440	12.98
S7-C100×50×2-R9-N75-F360	100	50	2	9	75	465	13.81
S7-C150×50×2-R9-N25-F360	150	50	2	9	25	565	11.51
S7-C150×50×2-R9-N50-F360	150	50	2	9	50	590	12.67
S7-C150×50×2-R9-N75-F360	150	50	2	9	75	615	13.62
S7-C200×50×2-R9-N25-F360	200	50	2	9	25	715	11.33
S7-C200×50×2-R9-N50-F360	200	50	2	9	50	740	12.49
S7-C200×50×2-R9-N75-F360	200	50	2	9	75	765	13.26
S7-C250×50×2-R9-N25-F360	250	50	2	9	25	865	11.03
S7-C250×50×2-R9-N50-F360	250	50	2	9	50	890	12.25
S7-C250×50×2-R9-N75-F360	250	50	2	9	75	915	13.20

Table 4.8 Specimen dimensions and finite element web crippling strength P_{FE} for Series S8

Specimen Label	Web d mm	Flanges b mm	Thickness t mm	Radius R mm	Bearing N mm	Length L mm	P_{FE} kN
S8-C100×50×3-R9-N25-F360	100	50	3	9	25	415	20.45
S8-C100×50×3-R9-N50-F360	100	50	3	9	50	440	24.14
S8-C100×50×3-R9-N75-F360	100	50	3	9	75	465	27.22
S8-C150×50×3-R9-N25-F360	150	50	3	9	25	565	20.44
S8-C150×50×3-R9-N50-F360	150	50	3	9	50	590	24.14
S8-C150×50×3-R9-N75-F360	150	50	3	9	75	615	27.20
S8-C200×50×3-R9-N25-F360	200	50	3	9	25	715	20.34
S8-C200×50×3-R9-N50-F360	200	50	3	9	50	740	23.84
S8-C200×50×3-R9-N75-F360	200	50	3	9	75	765	27.11
S8-C250×50×3-R9-N25-F360	250	50	3	9	25	865	20.24
S8-C250×50×3-R9-N50-F360	250	50	3	9	50	890	23.61
S8-C250×50×3-R9-N75-F360	250	50	3	9	75	915	26.94

The maximum and minimum predicted web crippling load was highlighted for each modeled series as shown in the previous tables. Dividing the 8 series into two groups according to the material yield stress would show that, for series S1, S2, S3 and S4 the minimum predicted web crippling load was 7.90 kN, while the maximum was 19.59 kN. The minimum value belongs to specimen labeled "S3-C250×50×2-R9-N25-F240" which had (h/t = 114.0, N/t = 12.5) and the highest ratio (R/t = 4.5). On the other hand, for the same group the maximum value belongs to specimen labeled "S2-C100×50×3-R6-N75-F240" which had (h/t = 27.3, N/t = 25) and the lowest ratio (R/t = 2.0).

For series S5, S6, S7 and S8 the minimum predicted web crippling load was 11.03 kN, while the maximum was 28.92 kN. The minimum value belongs to specimen labeled "S7-C250×50×2-R9-N25-F360" which had (h/t = 114.0, N/t = 12.5) and the highest ratio (R/t = 4.5). On the other hand, for the same group the maximum value belongs to specimen labeled "S6-C100×50×3-R6-N75-F360" which had (h/t = 27.3, N/t = 25) and the lowest ratio (R/t = 2.0).

4.3 Parametric Study on Web Crippling

It was clear from the literature that, the web crippling strength of cold formed steel sections is a function of mainly five parameters which are: web thickness (t), material yield strength (F_y), web slenderness (h/t), bearing length to thickness ratio (N/t) and inside bend radius to thickness ratio (R/t). In the following sections the five parameters effect on the web crippling strength is discussed in light of the analysis results of web crippling models.

4.3.1 Thickness (t)

The web thickness (t) is considered as a main factor that controls the web crippling strength because all other factors except for the material yield strength are related to it. Figure 4.17 through 4.20 show the effect of changing the web thickness from 2 mm to 3 mm on the web crippling strength. In the following figures the vertical axes represents the web crippling ultimate load in (kN) and the horizontal axis represents the dimensionless ratio (N/R). Where (N) is the bearing load length and (R) is the inside bend radius of cold formed channel section. It is observed that changing the web thickness from 2 to 3 mm resulted in an increase in the web crippling capacity in range of (75 to 112%) with a mean value of (95%). It is also observed that the rate of increasing the web crippling strength is directly proportioned with increasing the bearing length (N).

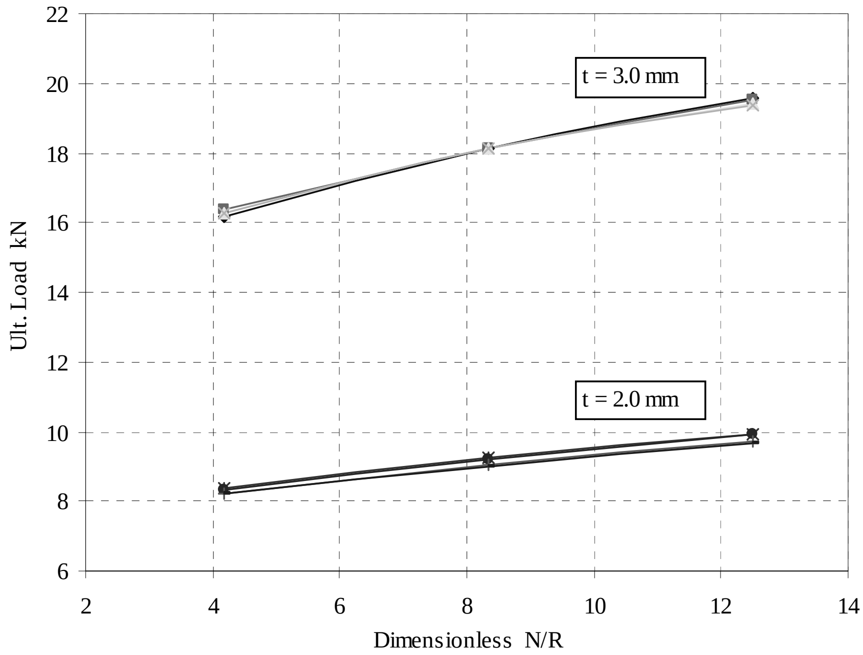

Fig. 4.17 Load versus dimensionless ratio N/R for series S1&S2

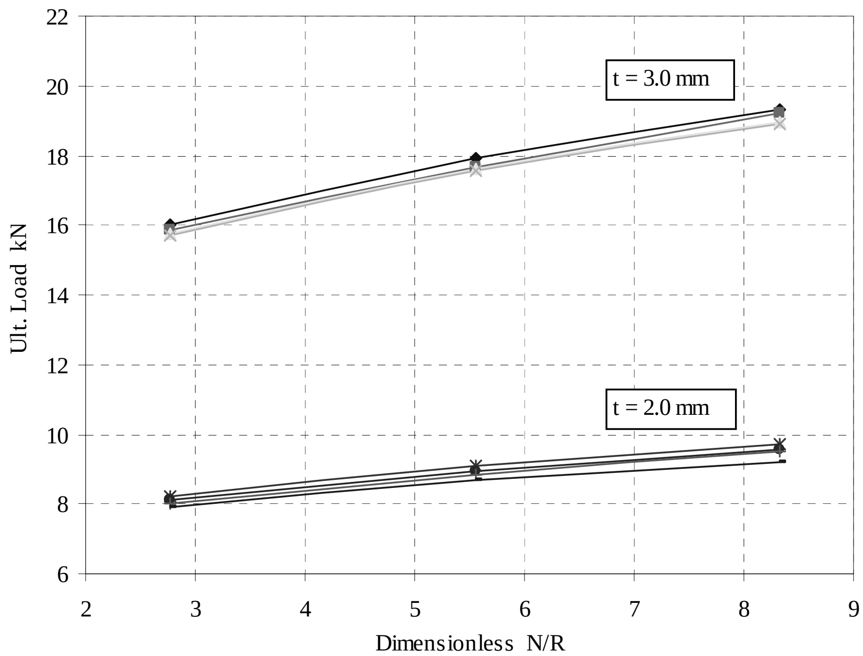

Fig. 4.18 Load versus dimensionless ratio N/R for series S3&S4

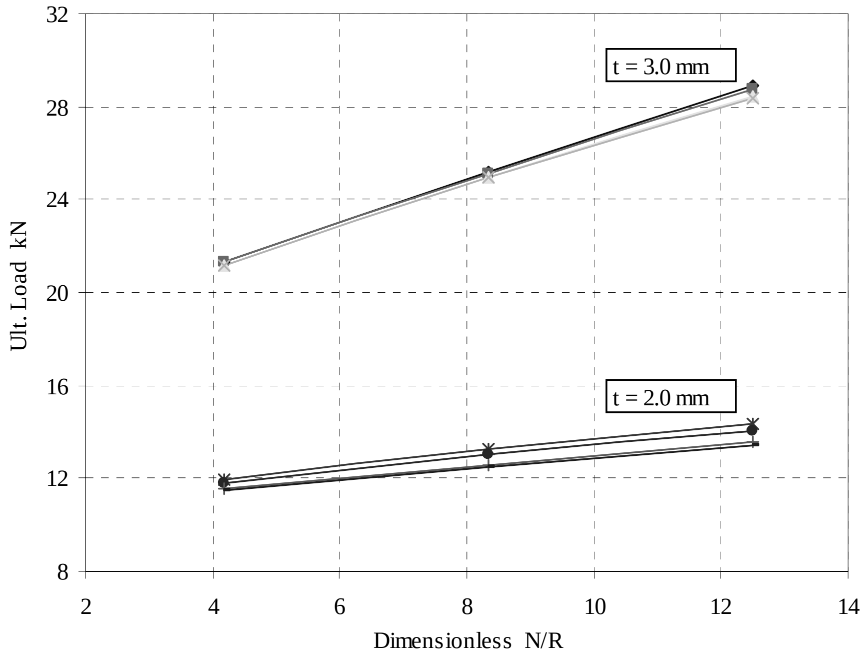

Fig. 4.19 Load versus dimensionless ratio N/R for series S5&S6

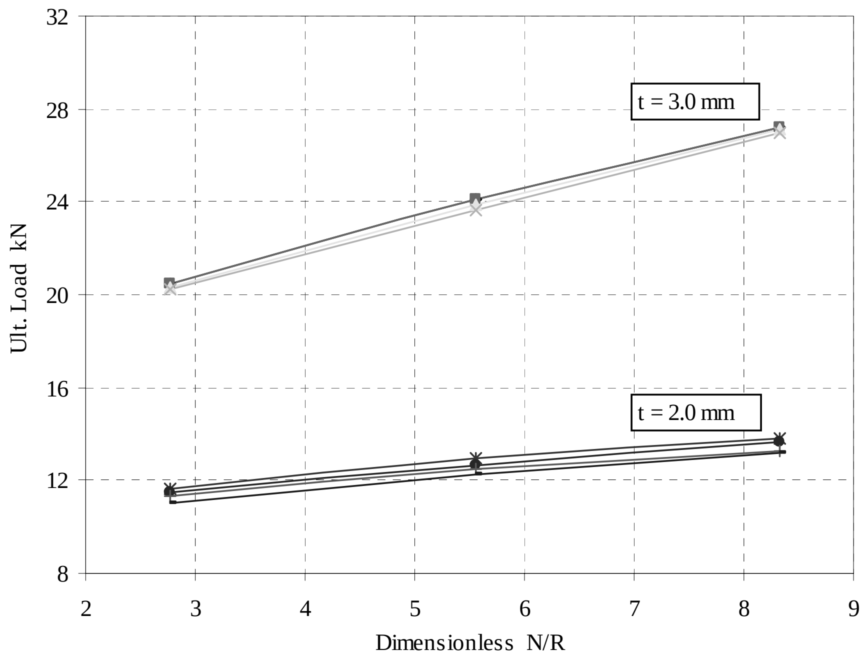

Fig. 4.20 Load versus dimensionless ratio N/R for series S7&S8

4.3.2 Material Yield Strength (F_y)

Figure 4.21 through 4.24 present the influence of changing the material yield strength (F_y) on the web crippling resistance. The vertical axis represents the ultimate load and the horizontal axis represents the bearing load length to thickness ratio (N/t). It is observed that, increasing the material yield strength from 240 to 360 N/mm^2 with keeping all other factors (t, h/t, N/t and R/t) constant resulted in an increase in the web crippling resistance by about (39%).

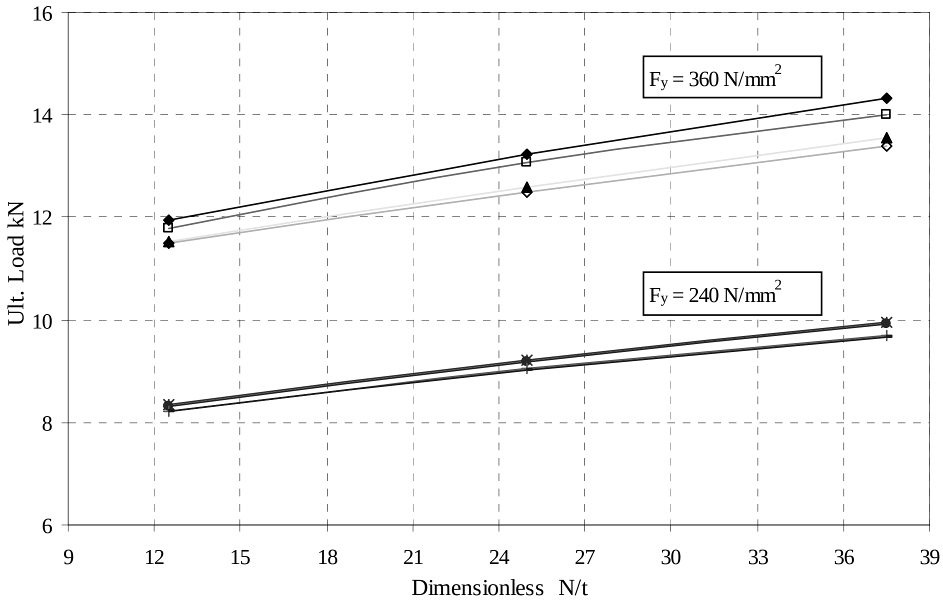

Fig. 4.21 Load versus dimensionless ratio N/t for series S1&S5

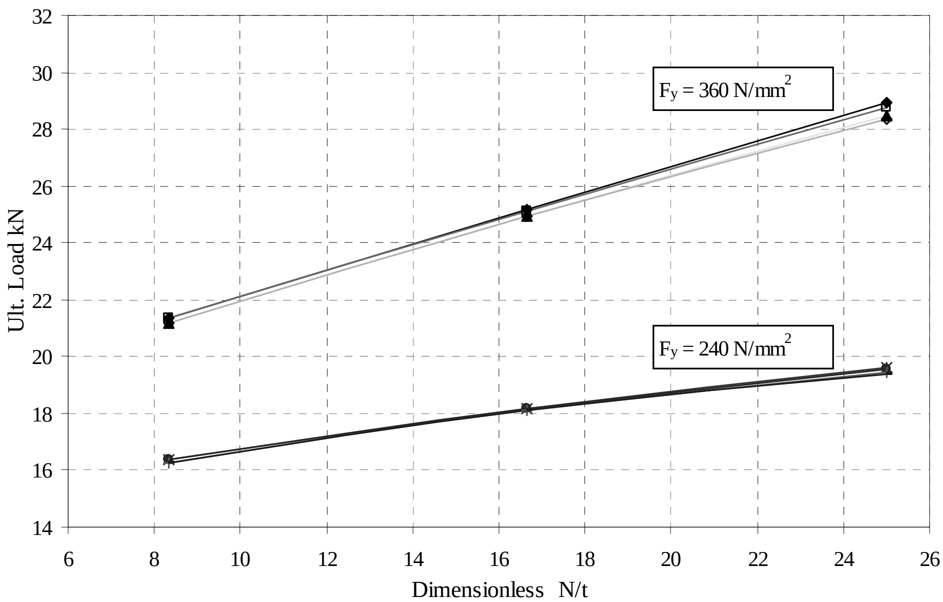

Fig. 4.22 Load versus dimensionless ratio N/t for series S2&S6

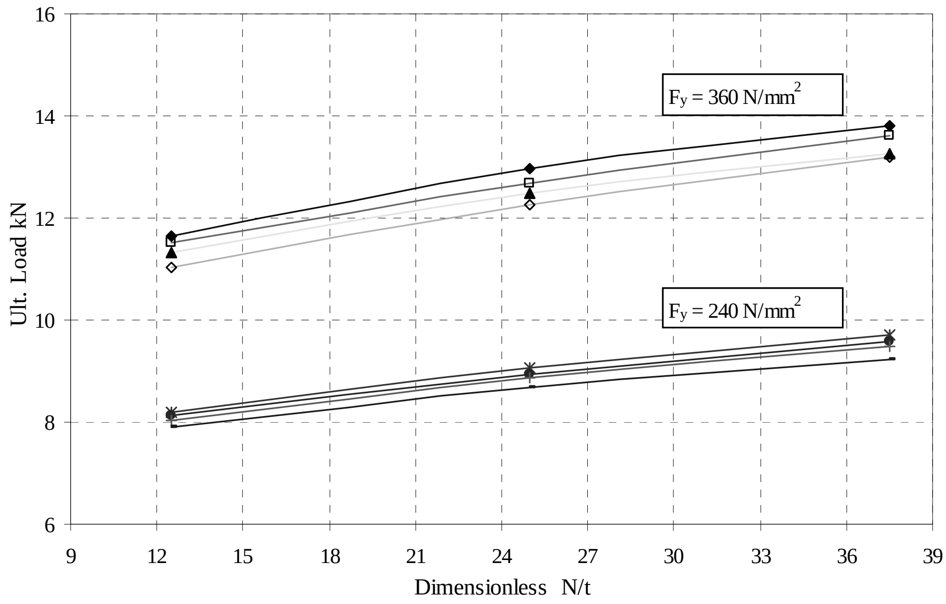

Fig. 4.23 Load versus dimensionless ratio N/t for series S3&S7

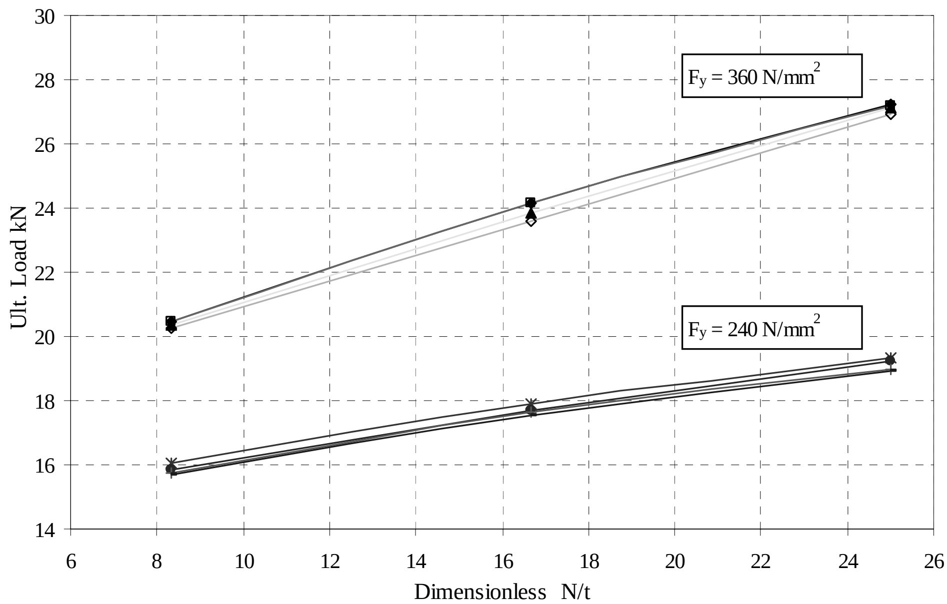

Fig. 4.24 Load versus dimensionless ratio N/t for series S4&S8

4.3.3 Web Slenderness (h/t)

Reviewing Figures 4.17 to 4.24, one can observe that changing the web depth (d) has a small effect on the web crippling ultimate load. This conclusion may be concerned only with the studied case of loading which represents interior one flange loading.

4.3.4 Bearing Length to Thickness Ratio (N/t)

Figure 4.25 through 4.32 show the relation between the ultimate load represented on the vertical axis and the bearing load length to thickness ratio (N/t) represented on the horizontal axis. It is observed that, increasing the bearing load length from 25 to 50 mm resulted in an increase in the web crippling capacity of about 12% and an increase of about 23% was achieved when the bearing load length increased from 25 to 75 mm.

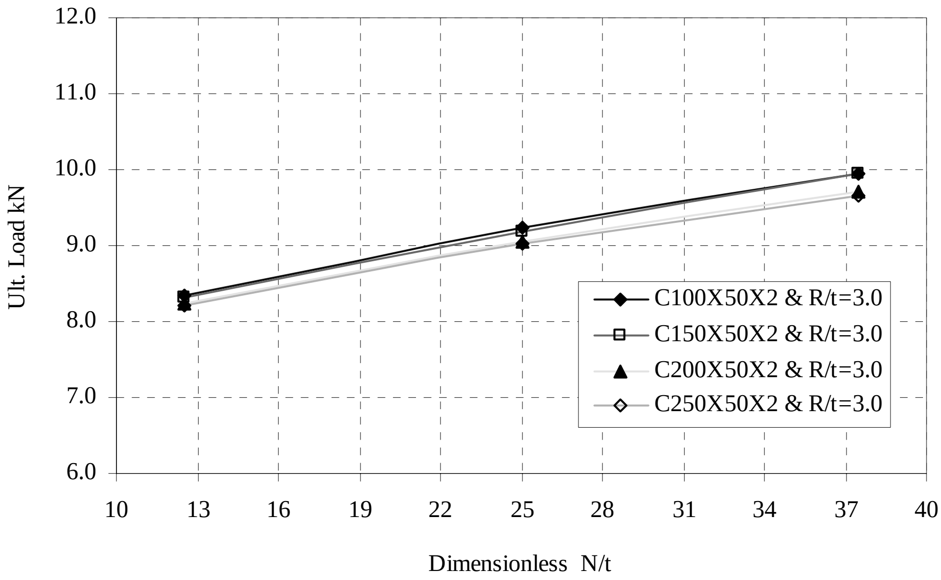

Fig. 4.25 Finite element load versus dimensionless ratio N/t for series S1

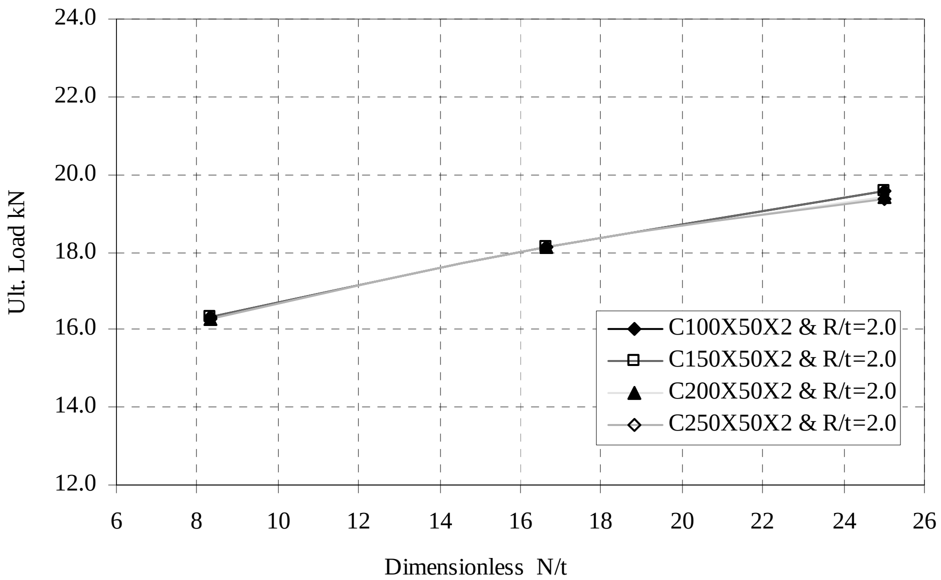

Fig. 4.26 Finite element loads versus dimensionless ratio N/t for series S2

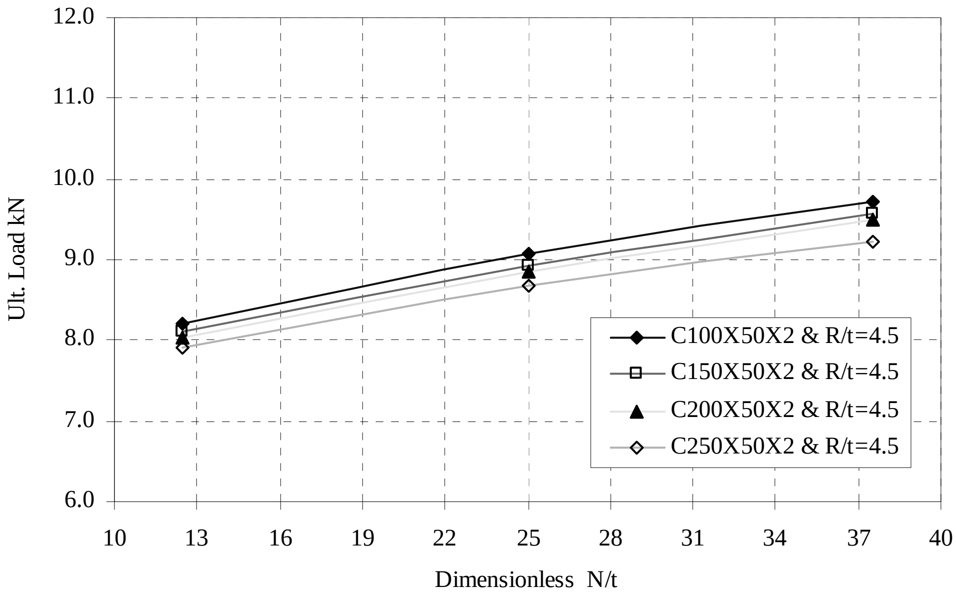

Fig. 4.27 Finite element loads versus dimensionless ratio N/t for series S3

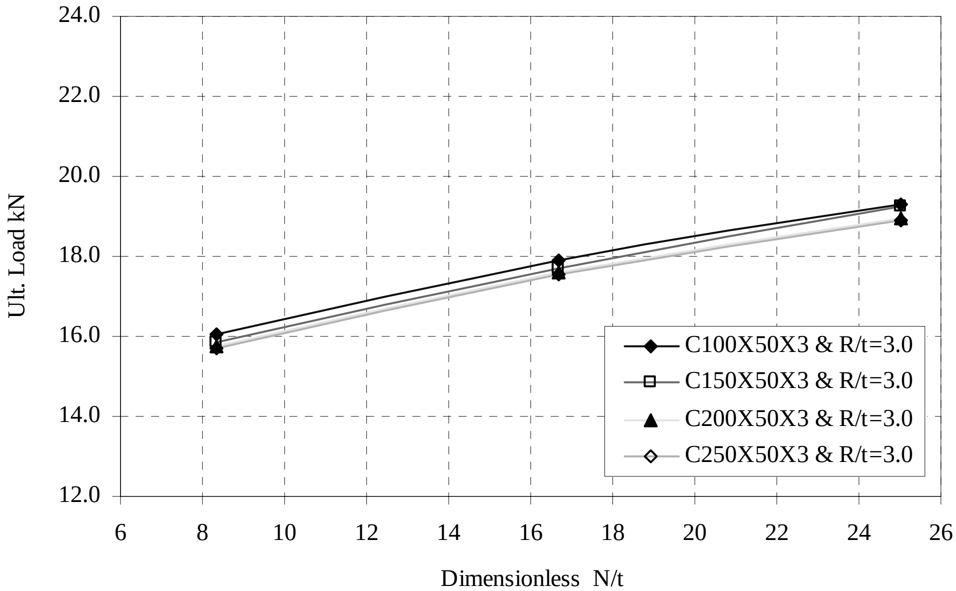

Fig. 4.28 Finite element loads versus dimensionless ratio N/t for series S4

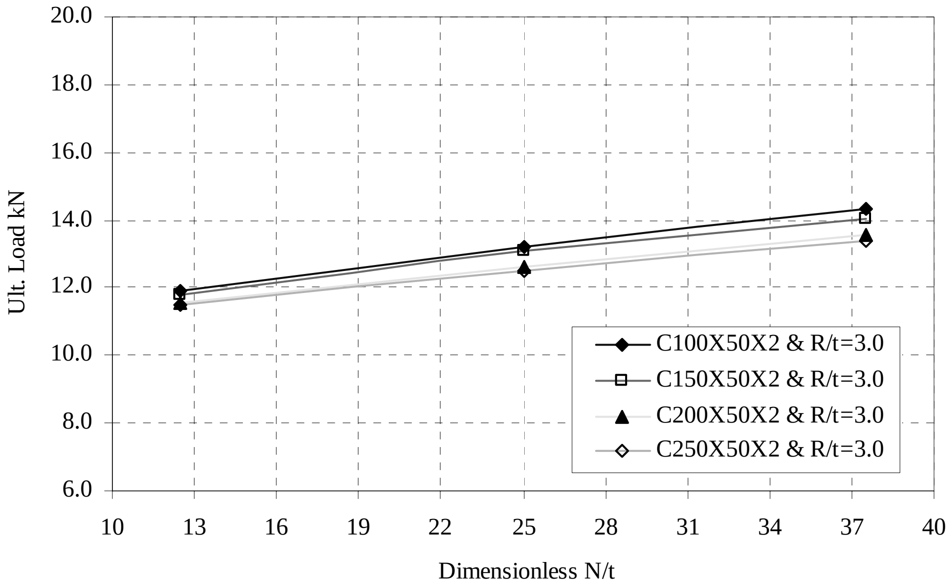

Fig. 4.29 Finite element loads versus dimensionless ratio N/t for series S5

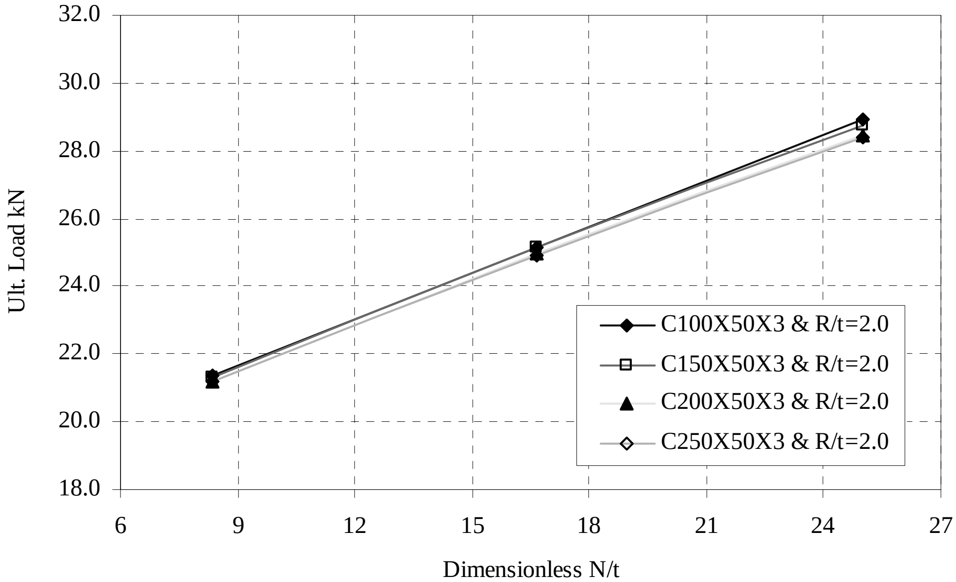

Fig. 4.30 Finite element loads versus dimensionless ratio N/t for series S6

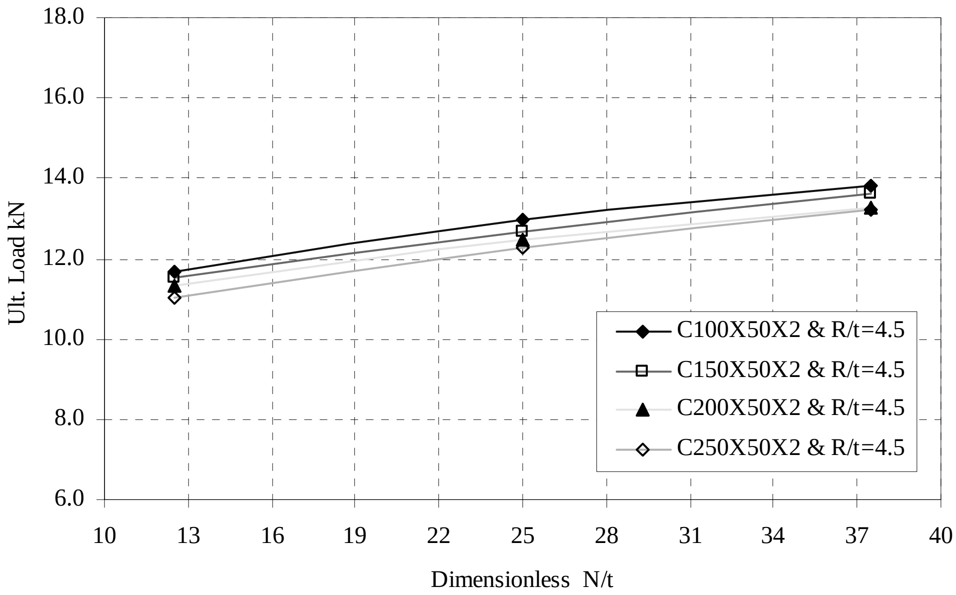

Fig. 4.31 Finite element loads versus dimensionless ratio N/t for series S7

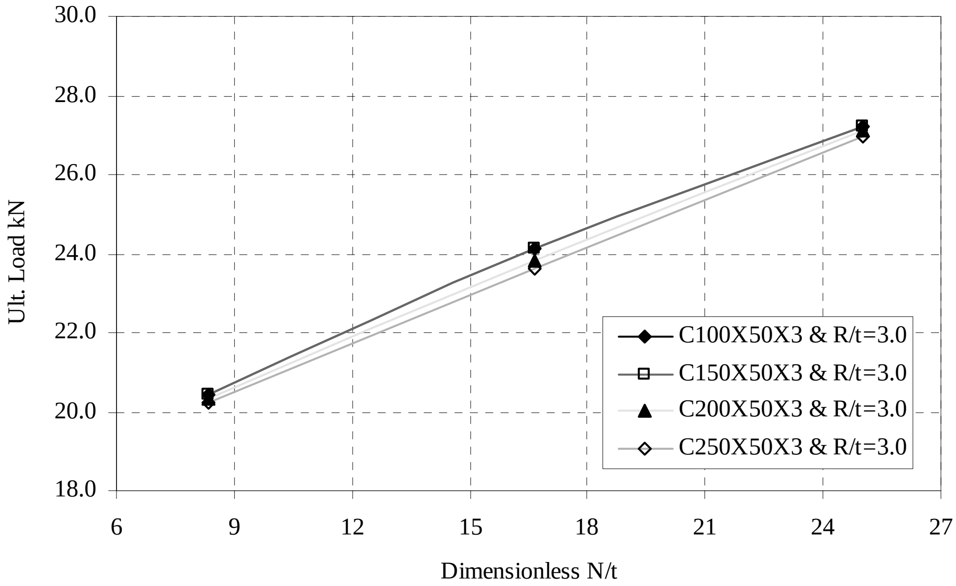

Fig. 4.32 Finite element loads versus dimensionless ratio N/t for series S8

4.3.5 Bend Radius to Thickness Ratio (R/t)

Figs. 4.33-4.36 show the influence of changing the inside bend radius to thickness ratio for a pair of models have the same thicknesses and material yield strength. It is noted that increasing (R/t) by 50% results in decreasing the ultimate web crippling capacity by about 3%.

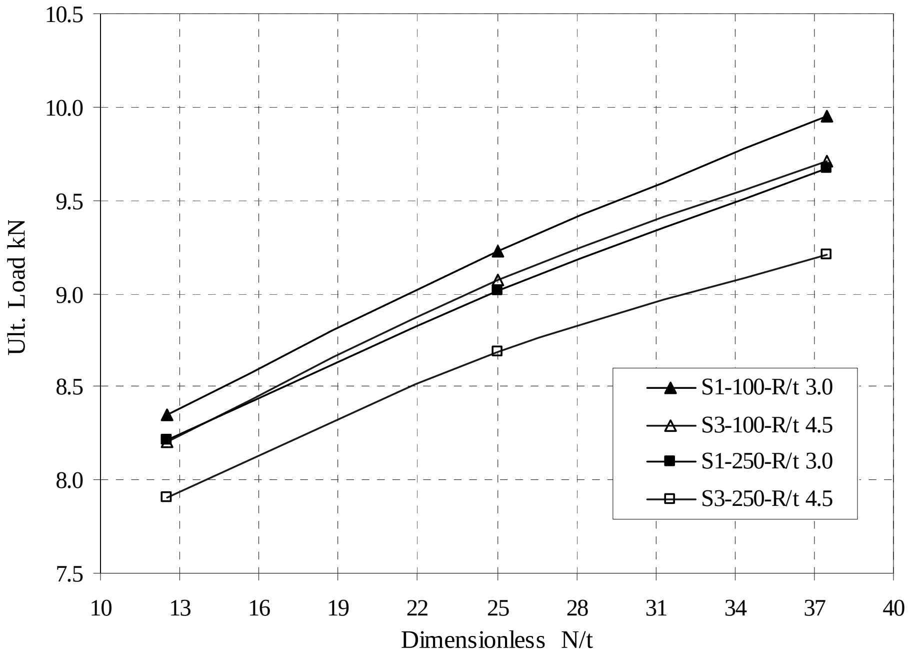

Fig. 4.33 Load versus dimensionless ratio N/t for series S1&S3

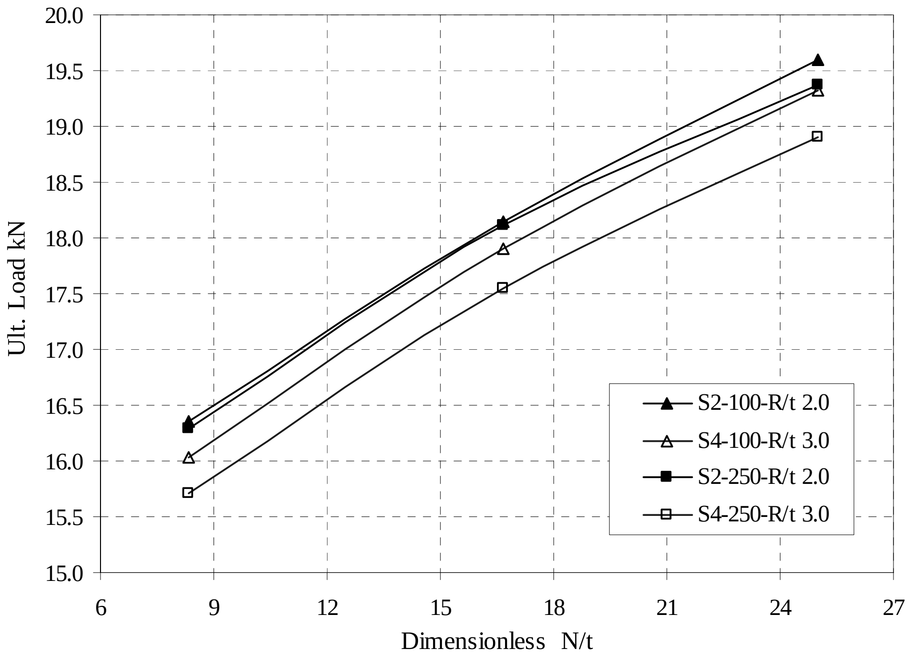

Fig. 4.34 Load versus dimensionless ratio N/t for series S2&S4

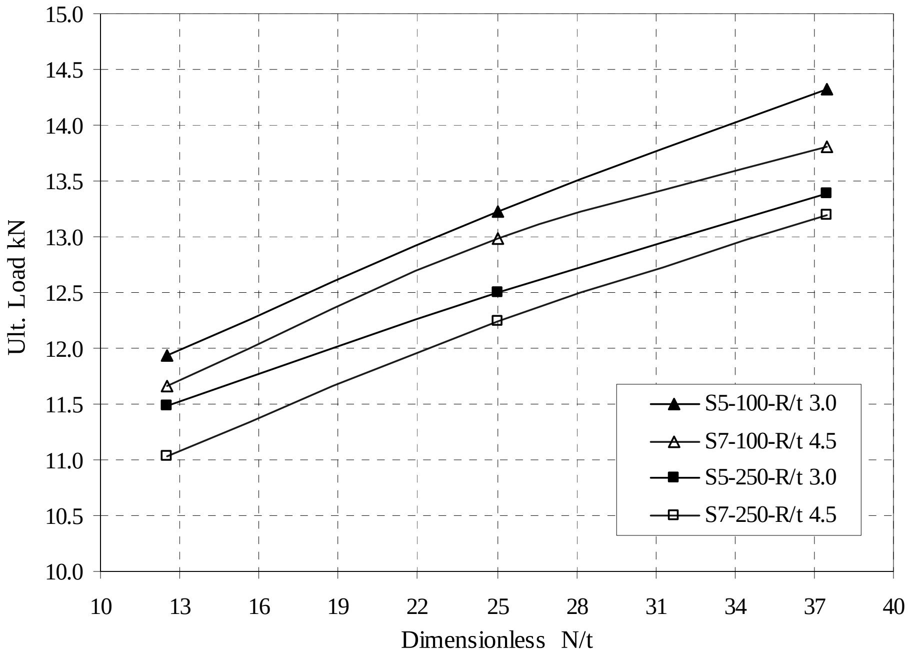

Fig. 4.35 Load versus dimensionless ratio N/t for series S5&S7

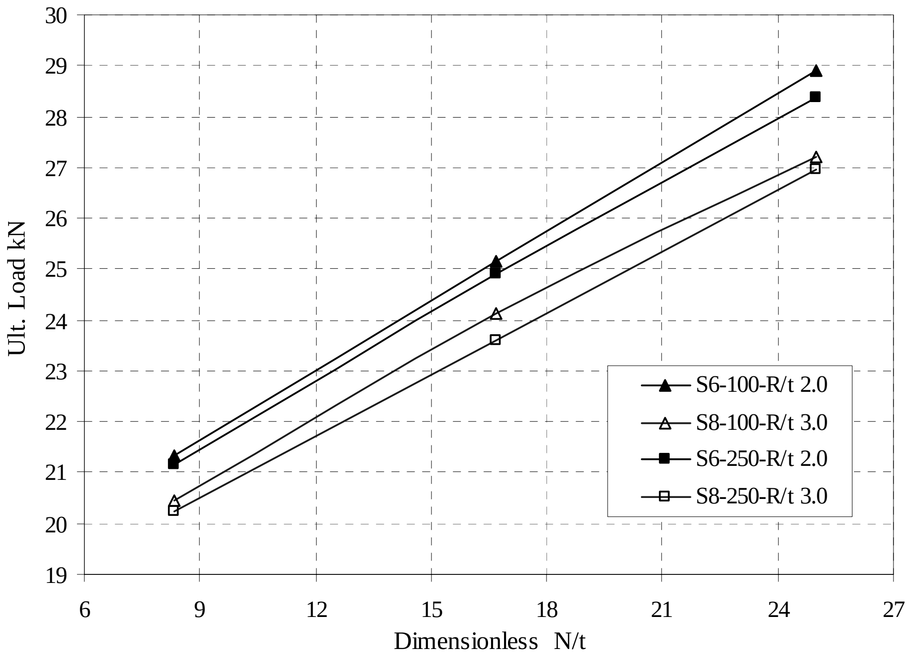

Fig. 4.36 Load versus dimensionless ratio N/t for series S6&S8

Reviewing Figs 4.17 to 4.36, one can realize that the main factors controlling the web crippling resistance of the studied C-sections are; the web thickness (t), the material yield strength (F_y) and the bearing load length to thickness ratio (N/t). On the other hand, the inside bend radius to thickness ratio (R/t) and the web slenderness (h/t) have a small effect on the predicted web crippling resistance.

4.4 Finite Element Web Crippling Strengths versus Design Codes

The web crippling strengths from finite element analysis of pure web crippling models were compared with the nominal web crippling strengths calculated from Australian/New Zealand Standard AS/NZS 4600, Britain Standard BS 5950-5, Egyptian code ECP-LRFD and North American Specification NAS. Although NAS was not applicable for un-stiffened C-sections with inside bend radius to thickness ratios > 1.0, it was involved in the comparison to check the validity of using it for the studied range of parameters.

In Tables 4.9 to 4.16, comparisons of the finite element strengths (P_{FE}) of the modeled channels with the nominal design strengths (P_n or P_w) were presented.

Table 4.9 Comparison of Finite Element Web Crippling strength P_{FE} with Current design strengths for series S1

Specimen Label	Ratio				P_{FE} kN	*NAS P_n kN	ECP P_n kN	BS P_w kN	AS/NZS P_n kN	Comparison			
	D/t	h/t	N/t	R/t						$\frac{P_{FE}}{P_{NAS}}$	$\frac{P_{FE}}{P_{ECP}}$	$\frac{P_{FE}}{P_{BS}}$	$\frac{P_{FE}}{P_{AS/NZS}}$
S1-C100×50N25	50.0	42.0	12.5	3.0	8.35	7.04	11.27	12.43	13.85	1.19	0.74	0.67	0.60
S1-C100×50N50	50.0	42.0	25.0	3.0	9.23	7.80	11.44	13.43	14.96	1.18	0.81	0.69	0.62
S1-C100×50N75	50.0	42.0	37.5	3.0	9.95	8.39	11.61	14.43	16.08	1.19	0.86	0.69	0.62
S1-C150×50N25	75.0	67.0	12.5	3.0	8.32	6.91	10.86	11.97	13.34	1.20	0.77	0.69	0.62
S1-C150×50N50	75.0	67.0	25.0	3.0	9.19	7.66	11.02	12.93	14.42	1.20	0.83	0.71	0.64
S1-C150×50N75	75.0	67.0	37.5	3.0	9.94	8.24	11.18	13.89	15.49	1.21	0.89	0.72	0.64
S1-C200×50N25	100.0	92.0	12.5	3.0	8.23	6.81	10.45	11.51	12.84	1.21	0.79	0.72	0.64
S1-C200×50N50	100.0	92.0	25.0	3.0	9.06	7.54	10.61	12.44	13.87	1.20	0.85	0.73	0.65
S1-C200×50N75	100.0	92.0	37.5	3.0	9.71	8.11	10.76	13.36	14.91	1.20	0.90	0.73	0.65
S1-C250×50N25	125.0	117.0	12.5	3.0	8.22	6.72	10.04	11.05	12.33	1.22	0.82	0.74	0.67
S1-C250×50N50	125.0	117.0	25.0	3.0	9.02	7.44	10.19	11.94	13.33	1.21	0.88	0.75	0.68
S1-C250×50N75	125.0	117.0	37.5	3.0	9.67	8.00	10.34	12.83	14.32	1.21	0.94	0.75	0.68

* Not applicable for R/t > 1.0

Table 4.10 Comparison of Finite Element Web Crippling strength P_{FE} with Current design strengths for series S2

Specimen Label	Ratio				P_{FE} kN	*NAS P_n kN	ECP P_n kN	BS P_w kN	AS/NZS P_n kN	Comparison			
	D/t	h/t	N/t	R/t						$\frac{P_{FE}}{P_{NAS}}$	$\frac{P_{FE}}{P_{ECP}}$	$\frac{P_{FE}}{P_{BS}}$	$\frac{P_{FE}}{P_{AS/NZS}}$
S2-C100×50N25	33.3	27.3	8.3	2.0	16.35	18.77	27.54	29.78	33.09	0.87	0.59	0.55	0.49
S2-C100×50N50	33.3	27.3	16.7	2.0	18.14	20.52	27.81	31.42	34.91	0.88	0.65	0.58	0.52
S2-C100×50N75	33.3	27.3	25.0	2.0	19.59	21.85	28.08	33.06	36.74	0.90	0.70	0.59	0.53
S2-C150×50N25	50.0	44.0	8.3	2.0	16.35	18.50	26.88	29.06	32.30	0.88	0.61	0.56	0.51
S2-C150×50N50	50.0	44.0	16.7	2.0	18.14	20.21	27.15	30.67	34.08	0.90	0.67	0.59	0.53
S2-C150×50N75	50.0	44.0	25.0	2.0	19.55	21.53	27.42	32.27	35.86	0.91	0.71	0.61	0.55
S2-C200×50N25	66.7	60.7	8.3	2.0	16.29	18.27	26.23	28.35	31.51	0.89	0.62	0.57	0.52
S2-C200×50N50	66.7	60.7	16.7	2.0	18.12	19.96	26.49	29.91	33.25	0.91	0.68	0.61	0.54
S2-C200×50N75	66.7	60.7	25.0	2.0	19.44	21.26	26.75	31.48	34.99	0.91	0.73	0.62	0.56
S2-C250×50N25	83.3	77.3	8.3	2.0	16.29	18.07	25.57	27.64	30.72	0.90	0.64	0.59	0.53
S2-C250×50N50	83.3	77.3	16.7	2.0	18.11	19.74	25.83	29.16	32.42	0.92	0.70	0.62	0.56
S2-C250×50N75	83.3	77.3	25.0	2.0	19.36	21.03	26.08	30.68	34.11	0.92	0.74	0.63	0.57

* Not applicable for R/t > 1.0

Table 4.11 Comparison of Finite Element Web Crippling strength P_{FE} with Current design strengths for series S3

Specimen Label	Ratio				P_{FE} kN	*NAS P_n kN	ECP P_n kN	BS P_w kN	AS/NZS P_n kN	Comparison			
	D/t	h/t	N/t	R/t						$\frac{P_{FE}}{P_{NAS}}$	$\frac{P_{FE}}{P_{ECP}}$	$\frac{P_{FE}}{P_{BS}}$	$\frac{P_{FE}}{P_{AS/NZS}}$
S3-C100×50N25	50.0	39.0	12.5	4.5	8.21	5.09	10.17	11.16	12.49	1.61	0.81	0.74	0.66
S3-C100×50N50	50.0	39.0	25.0	4.5	9.07	5.64	10.32	12.05	13.49	1.61	0.88	0.75	0.67
S3-C100×50N75	50.0	39.0	37.5	4.5	9.71	6.06	10.47	12.95	14.50	1.60	0.93	0.75	0.67
S3-C150×50N25	75.0	64.0	12.5	4.5	8.11	4.99	9.80	10.74	12.03	1.63	0.83	0.76	0.67
S3-C150×50N50	75.0	64.0	25.0	4.5	8.94	5.53	9.94	11.61	13.00	1.62	0.90	0.77	0.69
S3-C150×50N75	75.0	64.0	37.5	4.5	9.57	5.95	10.09	12.47	13.97	1.61	0.95	0.77	0.69
S3-C200×50N25	100.0	89.0	12.5	4.5	8.02	4.91	9.43	10.33	11.58	1.63	0.85	0.78	0.69
S3-C200×50N50	100.0	89.0	25.0	4.5	8.86	5.45	9.57	11.16	12.51	1.63	0.93	0.79	0.71
S3-C200×50N75	100.0	89.0	37.5	4.5	9.48	5.85	9.71	12.00	13.44	1.62	0.98	0.79	0.71
S3-C250×50N25	125.0	114.0	12.5	4.5	7.90	4.85	9.06	9.92	11.13	1.63	0.87	0.80	0.71
S3-C250×50N50	125.0	114.0	25.0	4.5	8.69	5.37	9.19	10.72	12.02	1.62	0.95	0.81	0.72
S3-C250×50N75	125.0	114.0	37.5	4.5	9.21	5.77	9.33	11.52	12.92	1.60	0.99	0.80	0.71

* Not applicable for R/t > 1.0

Table 4.12 Comparison of Finite Element Web Crippling strength P_{FE} with Current design strengths for series S4

Specimen Label	Ratio				P_{FE} kN	*NAS P_n kN	ECP P_n kN	BS P_w kN	AS/NZS P_n kN	Comparison			
	D/t	h/t	N/t	R/t						$\frac{P_{FE}}{P_{NAS}}$	$\frac{P_{FE}}{P_{ECP}}$	$\frac{P_{FE}}{P_{BS}}$	$\frac{P_{FE}}{P_{AS/NZS}}$
S4-C100×50N25	33.3	25.3	8.3	3.0	16.03	15.32	25.85	27.88	31.06	1.05	0.62	0.57	0.52
S4-C100×50N50	33.3	25.3	16.7	3.0	17.91	16.74	26.11	29.41	32.78	1.07	0.69	0.61	0.55
S4-C100×50N75	33.3	25.3	25.0	3.0	19.32	17.83	26.37	30.95	34.49	1.08	0.73	0.62	0.56
S4-C150×50N25	50.0	42.0	8.3	3.0	15.83	15.08	25.24	27.21	30.33	1.05	0.63	0.58	0.52
S4-C150×50N50	50.0	42.0	16.7	3.0	17.68	16.48	25.49	28.71	32.00	1.07	0.69	0.62	0.55
S4-C150×50N75	50.0	42.0	25.0	3.0	19.24	17.56	25.74	30.21	33.67	1.10	0.75	0.64	0.57
S4-C200×50N25	66.7	58.7	8.3	3.0	15.74	14.89	24.63	26.54	29.59	1.06	0.64	0.59	0.53
S4-C200×50N50	66.7	58.7	16.7	3.0	17.62	16.28	24.87	28.00	31.22	1.08	0.71	0.63	0.56
S4-C200×50N75	66.7	58.7	25.0	3.0	18.97	17.34	25.12	29.47	32.85	1.09	0.76	0.64	0.58
S4-C250×50N25	83.3	75.3	8.3	3.0	15.71	14.73	24.02	25.87	28.85	1.07	0.65	0.61	0.54
S4-C250×50N50	83.3	75.3	16.7	3.0	17.55	16.10	24.25	27.30	30.44	1.09	0.72	0.64	0.58
S4-C250×50N75	83.3	75.3	25.0	3.0	18.90	17.15	24.49	28.72	32.03	1.10	0.77	0.66	0.59

* Not applicable for R/t > 1.0

Table 4.13 Comparison of Finite Element Web Crippling strength PFE with Current design strengths for series S5

Specimen Label	Ratio					*NAS	ECP	BS	AS/NZS	Comparison			
	D/t	h/t	N/t	R/t	P_{FE} kN	P_n kN	P_n kN	P_w kN	P_n kN	$\frac{P_{FE}}{P_{NAS}}$	$\frac{P_{FE}}{P_{ECP}}$	$\frac{P_{FE}}{P_{BS}}$	$\frac{P_{FE}}{P_{AS/NZS}}$
S5-C100×50N25	50.0	42.0	12.5	3.0	11.94	10.56	14.84	16.46	18.36	1.13	0.80	0.73	0.65
S5-C100×50N50	50.0	42.0	25.0	3.0	13.23	11.71	15.06	17.78	19.84	1.13	0.88	0.74	0.67
S5-C100×50N75	50.0	42.0	37.5	3.0	14.32	12.58	15.28	19.10	21.31	1.14	0.94	0.75	0.67
S5-C150×50N25	75.0	67.0	12.5	3.0	11.78	10.37	14.30	15.85	17.69	1.14	0.82	0.74	0.67
S5-C150×50N50	75.0	67.0	25.0	3.0	13.06	11.49	14.51	17.12	19.11	1.14	0.90	0.76	0.68
S5-C150×50N75	75.0	67.0	37.5	3.0	14.01	12.35	14.72	18.40	20.53	1.13	0.95	0.76	0.68
S5-C200×50N25	100.0	92.0	12.5	3.0	11.54	10.21	13.76	15.24	17.02	1.13	0.84	0.76	0.68
S5-C200×50N50	100.0	92.0	25.0	3.0	12.60	11.32	13.96	16.47	18.39	1.11	0.90	0.76	0.69
S5-C200×50N75	100.0	92.0	37.5	3.0	13.57	12.16	14.17	17.70	19.76	1.12	0.96	0.77	0.69
S5-C250×50N25	125.0	117.0	12.5	3.0	11.48	10.07	13.22	14.64	16.35	1.14	0.87	0.78	0.70
S5-C250×50N50	125.0	117.0	25.0	3.0	12.51	11.16	13.41	15.81	17.66	1.12	0.93	0.79	0.71
S5-C250×50N75	125.0	117.0	37.5	3.0	13.38	12.00	13.61	16.99	18.98	1.12	0.98	0.79	0.71

* Not applicable for R/t > 1.0

Table 4.14 Comparison of Finite Element Web Crippling strength P_{FE} with Current design strengths for series S6

Specimen Label	Ratio				P_{FE} kN	*NAS P_n kN	ECP P_n kN	BS P_w kN	AS/NZS P_n kN	Comparison			
	D/t	h/t	N/t	R/t						$\frac{P_{FE}}{P_{NAS}}$	$\frac{P_{FE}}{P_{ECP}}$	$\frac{P_{FE}}{P_{BS}}$	$\frac{P_{FE}}{P_{AS/NZS}}$
S6-C100×50N25	33.3	27.3	8.3	2.0	21.34	28.16	36.25	39.44	43.86	0.76	0.59	0.54	0.49
S6-C100×50N50	33.3	27.3	16.7	2.0	25.17	30.77	36.61	41.61	46.28	0.82	0.69	0.60	0.54
S6-C100×50N75	33.3	27.3	25.0	2.0	28.92	32.78	36.97	43.78	48.69	0.88	0.78	0.66	0.59
S6-C150×50N25	50.0	44.0	8.3	2.0	21.33	27.74	35.39	38.49	42.81	0.77	0.60	0.55	0.50
S6-C150×50N50	50.0	44.0	16.7	2.0	25.12	30.32	35.74	40.61	45.17	0.83	0.70	0.62	0.56
S6-C150×50N75	50.0	44.0	25.0	2.0	28.76	32.29	36.09	42.73	47.53	0.89	0.80	0.67	0.61
S6-C200×50N25	66.7	60.7	8.3	2.0	21.18	27.40	34.53	37.54	41.77	0.77	0.61	0.56	0.51
S6-C200×50N50	66.7	60.7	16.7	2.0	24.96	29.94	34.87	39.61	44.07	0.83	0.72	0.63	0.57
S6-C200×50N75	66.7	60.7	25.0	2.0	28.45	31.89	35.21	41.68	46.37	0.89	0.81	0.68	0.61
S6-C250×50N25	83.3	77.3	8.3	2.0	21.16	27.10	33.66	36.60	40.72	0.78	0.63	0.58	0.52
S6-C250×50N50	83.3	77.3	16.7	2.0	24.92	29.62	34.00	38.62	42.97	0.84	0.73	0.65	0.58
S6-C250×50N75	83.3	77.3	25.0	2.0	28.38	31.55	34.33	40.63	45.21	0.90	0.83	0.70	0.63

* Not applicable for R/t > 1.0

Table 4.15 Comparison of Finite Element Web Crippling strength P_{FE} with Current design strengths for series S7

Specimen Label	Ratio				P_{FE} kN	*NAS P_n kN	ECP P_n kN	BS P_w kN	AS/NZS P_n kN	Comparison			
	D/t	h/t	N/t	R/t						$\frac{P_{FE}}{P_{NAS}}$	$\frac{P_{FE}}{P_{ECP}}$	$\frac{P_{FE}}{P_{BS}}$	$\frac{P_{FE}}{P_{AS/NZS}}$
S7-C100×50N25	50.0	39.0	12.5	4.5	11.66	7.63	13.38	14.77	16.55	1.53	0.87	0.79	0.70
S7-C100×50N50	50.0	39.0	25.0	4.5	12.98	8.46	13.58	15.96	17.88	1.53	0.96	0.81	0.73
S7-C100×50N75	50.0	39.0	37.5	4.5	13.81	9.09	13.78	17.15	19.22	1.52	1.00	0.81	0.72
S7-C150×50N25	75.0	64.0	12.5	4.5	11.51	7.49	12.90	14.23	15.95	1.54	0.89	0.81	0.72
S7-C150×50N50	75.0	64.0	25.0	4.5	12.67	8.30	13.09	15.37	17.23	1.53	0.97	0.82	0.73
S7-C150×50N75	75.0	64.0	37.5	4.5	13.62	8.92	13.28	16.52	18.52	1.53	1.03	0.82	0.74
S7-C200×50N25	100.0	89.0	12.5	4.5	11.33	7.37	12.41	13.68	15.35	1.54	0.91	0.83	0.74
S7-C200×50N50	100.0	89.0	25.0	4.5	12.49	8.17	12.59	14.79	16.59	1.53	0.99	0.84	0.75
S7-C200×50N75	100.0	89.0	37.5	4.5	13.26	8.78	12.78	15.89	17.82	1.51	1.04	0.83	0.74
S7-C250×50N25	125.0	114.0	12.5	4.5	11.03	7.27	11.92	13.14	14.75	1.52	0.93	0.84	0.75
S7-C250×50N50	125.0	114.0	25.0	4.5	12.25	8.06	12.10	14.20	15.94	1.52	1.01	0.86	0.77
S7-C250×50N75	125.0	114.0	37.5	4.5	13.20	8.66	12.28	15.25	17.12	1.52	1.07	0.87	0.77

* Not applicable for R/t > 1.0

Table 4.16 Comparison of Finite Element Web Crippling strength P_{FE} with Current design strengths for series S8

Specimen Label	Ratio					*NAS	ECP	BS	AS/NZS	Comparison			
	D/t	h/t	N/t	R/t	P_{FE} kN	P_n kN	P_n kN	P_w kN	P_n kN	$\frac{P_{FE}}{P_{NAS}}$	$\frac{P_{FE}}{P_{ECP}}$	$\frac{P_{FE}}{P_{BS}}$	$\frac{P_{FE}}{P_{AS/NZS}}$
S8-C100×50N25	33.3	25.3	8.3	3.0	20.45	22.98	34.03	36.92	41.18	0.89	0.60	0.55	0.50
S8-C100×50N50	33.3	25.3	16.7	3.0	24.14	25.11	34.37	38.95	43.45	0.96	0.70	0.62	0.56
S8-C100×50N75	33.3	25.3	25.0	3.0	27.22	26.74	34.71	40.99	45.72	1.02	0.78	0.66	0.60
S8-C150×50N25	50.0	42.0	8.3	3.0	20.44	22.63	33.23	36.03	40.20	0.90	0.62	0.57	0.51
S8-C150×50N50	50.0	42.0	16.7	3.0	24.14	24.73	33.56	38.02	42.41	0.98	0.72	0.63	0.57
S8-C150×50N75	50.0	42.0	25.0	3.0	27.20	26.34	33.88	40.01	44.63	1.03	0.80	0.68	0.61
S8-C200×50N25	66.7	58.7	8.3	3.0	20.34	22.34	32.42	35.15	39.22	0.91	0.63	0.58	0.52
S8-C200×50N50	66.7	58.7	16.7	3.0	23.84	24.41	32.74	37.08	41.38	0.98	0.73	0.64	0.58
S8-C200×50N75	66.7	58.7	25.0	3.0	27.11	26.01	33.06	39.02	43.54	1.04	0.82	0.69	0.62
S8-C250×50N25	83.3	75.3	8.3	3.0	20.24	22.09	31.61	34.26	38.24	0.92	0.64	0.59	0.53
S8-C250×50N50	83.3	75.3	16.7	3.0	23.61	24.14	31.93	36.15	40.35	0.98	0.74	0.65	0.59
S8-C250×50N75	83.3	75.3	25.0	3.0	26.94	25.72	32.24	38.04	42.46	1.05	0.84	0.71	0.63

* Not applicable for R/t > 1.0

In Figure 4.37, the finite element strengths (P_{EF}) were compared with the design strengths calculated using AS/NZS standard ($P_{AS/NZS}$). The vertical axis represents the load ratio ($P/P_{AS/NZS}$) of the finite element strength to the un-factored design strength calculated using AS/NZS standard. It was observed that, AS/NZS standard is inadequate for predicting the web crippling strengths for the studied range of parameters. The load ratios ranged from 0.49 to 0.77 with a mean value of 0.63, coefficient of variation 0.123 and reliability index (β) 0.80.

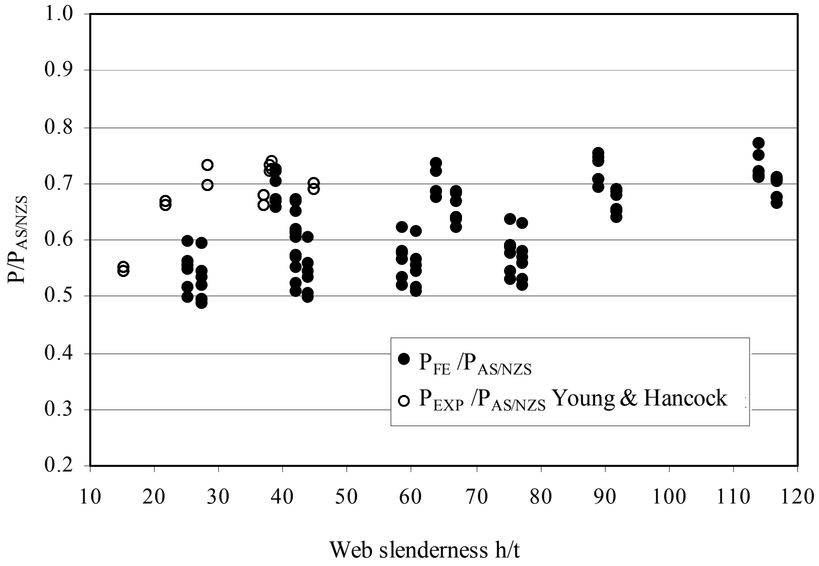

Fig. 4.37 Finite element strength versus design strength of AS/NZS

In Figure 4.38, the finite element strengths (P_{EF}) were compared with the design strengths calculated using BS standard (P_{BS}). The vertical axis represents the load ratio (P/ P_{BS}) of the finite element strength to the un-factored design strength calculated using BS standard. It was observed that, BS standard is inadequate for predicting the web crippling strengths for the studied range of parameters. The load ratios ranged from 0.54 to 0.87 with a mean value of 0.70, coefficient of variation 0.124 and reliability index (β) 1.20.

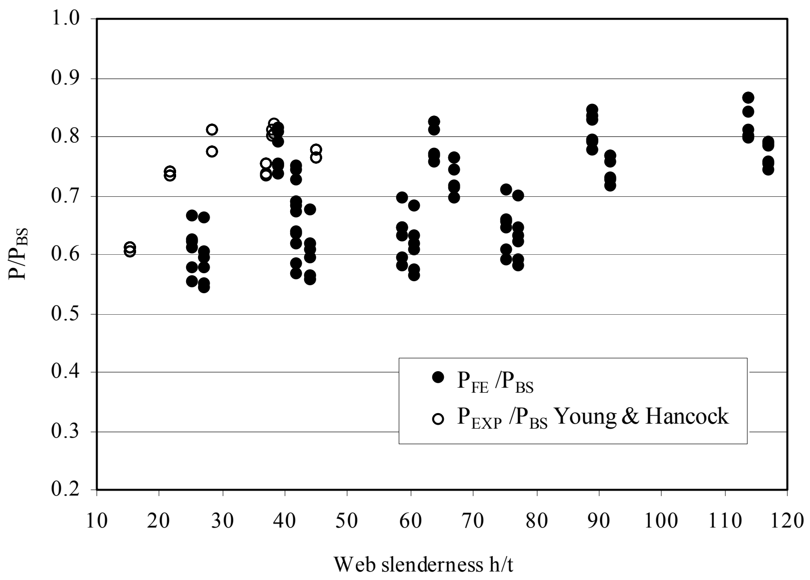

Fig. 4.38 Finite element strength versus design strength of BS

The finite element strengths (P_{EF}) were compared with the design strengths calculated using ECP (P_{ECP}) in Figure 4.39. The vertical axis represents the load ratio (P/ P_{ECP}) of the finite element strength to the un-factored design strength calculated using ECP. It was observed that, ECP design code is inadequate for predicting the web crippling strengths for the studied range of parameters. The load ratios ranged from 0.59 to 1.07 with a mean value of 0.81, coefficient of variation 0.147 and reliability index (β) 1.64.

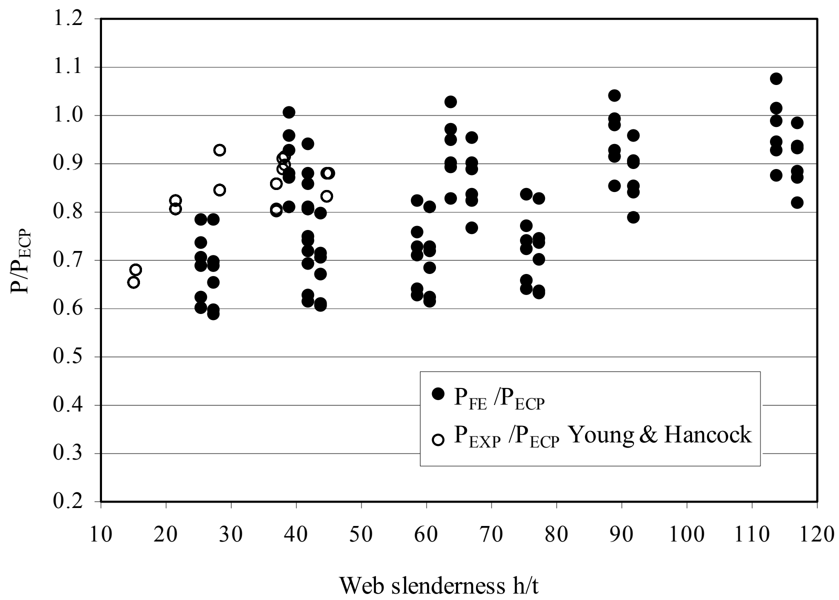

Fig. 4.39 Finite element strength versus design strength of ECP

The finite element strengths (P_{EF}) were compared with the design strengths calculated using NAS (P_{NAS}) in Figure 4.40. The vertical axis represents the load ratio (P/ P_{NAS}) of the finite element strength to the un-factored design strength calculated using NAS Specification. It was observed that, the design strengths predicted by NAS were acceptable for about 53% of specimens. The load ratios ranged from 0.66 to 1.63 with a mean value of 1.16, coefficient of variation 0.253 and reliability index (β) 2.18.

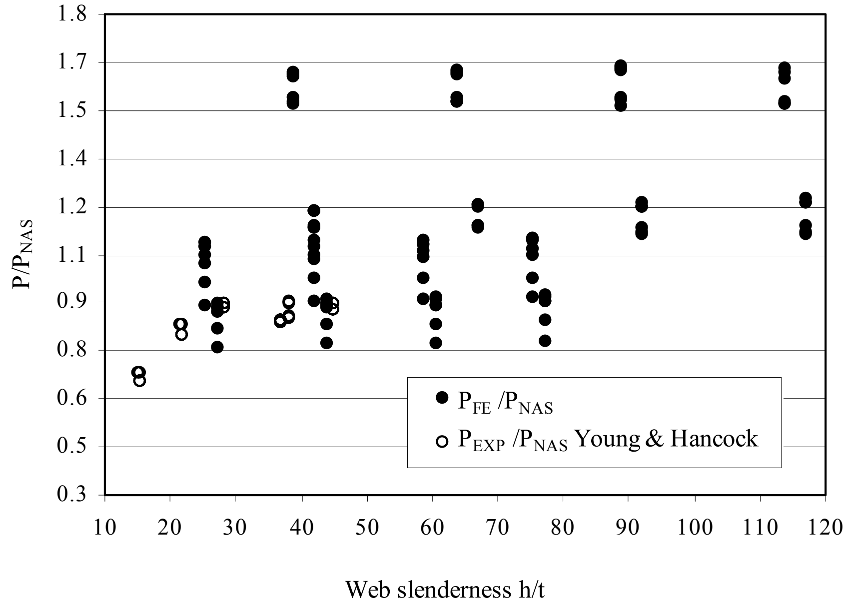

Fig. 4.40 Finite element strength versus design strength of NAS

Reviewing Figs 4.37-4.40, one can observe that both AS/NZS and BS standards are generally inadequate for predicting the web crippling strengths of the studied range of parameters. On the other hand, the NAS specification is inadequate for about 47% of data points and the predicted strengths using ECP is acceptable only for 4% of data points. Therefore, in the following sections new web crippling coefficients for both ECP and NAS specifications would be proposed and calibrated.

4.5 New Web Crippling Coefficients

In this section, new coefficients are proposed for the web crippling design equations of ECP and NAS specifications. The new coefficients are proposed to improve the prediction of web crippling strength for unstiffened C-sections subjected to IOF loading and unfastened through their flanges. The proposed coefficients are based on statistical analysis of 24 test data points from literature [41] in addition to the finite element analysis results of 96 web crippling models investigated in this research. The following proposed coefficients were obtained after several trials with different coefficient values to achieve as least coefficient of variation.

4.5.1 New Coefficients for ECP

In ECP, the web crippling resistance for shapes having single thickness webs subjected to IOF loading is calculated according to the following equation:

$$P_n = t^2\, k\, C_1\, C_2\, C_{12}\, C_{15}\, C_{19} \times 10^{-4} \qquad (2.23)$$

Where:

P_n = Nominal web strength in Tons

h = Flat web depth in mm

t = Web thickness in mm

k = $0.425\ F_y$

F_y = Design yield stress in t/cm^2

C_1 = $1.22 - 0.10F_y$

C_2 = $1.06 - 0.06(R/t) \leq 1.0$

R = Inside bend radius in mm

C_{12} = $0.70 + 0.3(\theta/90)^2$

θ = Angle between the web plane and the bearing surface plane

C_{15} = $3350 - 4.60(h/t)$

C_{19} = $1 + 0.0012(N/t)$

N = Actual length of bearing in mm

Based on statistical analysis of 24 test data points in literature [41] in addition to the finite element analysis results of 96 web crippling models, the following coefficients were updated:

C_1 = $1.15 - 0.001F_y$

C_2 = $1.05 - 0.05(R/t) \leq 1.0$

C_{15} = $1300 - 0.05(h/t)$

C_{19} = $1 + 0.02(N/t)$

4.5.2 New Coefficients for NAS

In NAS, the web crippling strength of single web C-sections is calculated according to the following expression:

$$P_n = C.\ t^2.\ Fy.\ \sin\theta \left(1 - C_R\sqrt{\frac{R}{t}}\right).\left(1 + C_N\sqrt{\frac{N}{t}}\right).\left(1 - C_h\sqrt{\frac{h}{t}}\right) \quad (2.17)$$

Where

P_n = Nominal web crippling strength / web (kN)

C = Coefficient for cross section shape from Table 2.1

t = Web thickness in mm

θ = Angle between the web plane and the bearing surface plane

F_y = Design yield stress (kN/mm^2)

C_R = Inside bend radius coefficient from Table 2.1

R = Inside bend radius

C_N = Bearing length coefficient from Table 2.1

N = Bearing length

C_h = Web slenderness coefficient from Table 2.1

h = Flat dimension of web measured in plane of web

Referring to Eq. 2.17, four coefficients were updated on basis of statistical analysis of 24 test data points from literature [41] in addition to the finite element analysis results of 96 web crippling models. The updated coefficients and the original coefficients specified in the NAS specification are listed in Table 4.17 for comparison purposes.

Table 4.17 Original and Updated Coefficients of the NAS design equation

	C	C_R	C_N	C_h
Original Coefficients	13	0.32	0.10	0.010
Updated Coefficients	6.5	0.15	0.15	0.001

4.5.3 Calibration of New Coefficients

There are two different design methods for cold formed steel structures, the Allowable Stress Design (ASD) and the Load and Resistance Factor Design (LRFD) method. The uncertainties in loads are overcome in the design by the resistance factor (Φ) in LRFD method and by factor of safety (Ω) in ASD method. Based on probabilistic concept the safety of the design can be measured in terms of reliability index β which depends on the critical load combinations, the structural element resistance, the fabrication variation and the material variation. In the NAS specification two values for the reliability index β are recommended; 2.5 for structural elements and 3.0 for connections. Based on reliability index β value of 2.5, the new coefficients were calibrated using Eq. 4.1 that defined in NAS specification as follows:

$$\sum \gamma_i Q_i = \phi R_n \qquad (4.1)$$

Where:

$\sum \gamma_i Q_i$ = Required strength [factored loads] based on the most critical load combination. γ_i and Q_i are load factors and load effects respectively.

ϕ = Resistance factor

$$\phi = C_\phi \cdot \left(M_m F_m P_m\right) \cdot \left(e^{-\beta\sqrt{V_M^2 + V_F^2 + C_P V_P^2 + V_Q^2}} \right) \qquad (4.2)$$

Where:

C_ϕ = Calibration coefficient, 1.52 for LRFD method

M_m = Mean value of material factor, from Table F1 in NAS

F_m = Mean value of fabrication factor, from Table F1 in NAS

P_m = Mean value of professional factor for tested component.

e = Natural logarithmic base, 2.718

β = Target reliability index

V_M = Coefficient of variation of material, from Table F1 in NAS

V_F = Coefficient of variation of fabrication, from Table F1 in NAS

C_P = Correction factor,

= $(1+1/n)m/(m-2)$ for $(n \geq 4)$

n = Number of tests

m = n-1

V_P = Coefficient of variation of test results, but not less than 6.5 percent

V_Q = Coefficient of variation of load effect, 0.21 for LRFD method

R_n = Average value of all test results

Substituting into Eq. 4.2 for β = 2.5, C_ϕ =1.52, e = 2.718 and V_Q = 0.21 the following equation is obtained:

$$\phi = 1.52 \cdot \left(M_m F_m P_m\right) \cdot \left(2.718^{-2.5\sqrt{V_M^2 + V_F^2 + C_P V_P^2 + 0.0441}}\right) \quad (4.3)$$

In Table F1 of NAS specification the following values are recommended for calibrating structural beam elements subjected to web crippling; M_m =1.1, F_m = 1.0, V_M = 0.1 and V_F = 0.05. Substituting into Eq. 4.3 the following equation is obtained:

$$\phi = 1.672 \cdot P_m \left(2.718^{-2.5\sqrt{0.0566 + C_P V_P^2}}\right) \quad (4.4)$$

Substituting for the number of tests n = 120 (24 test data points plus 96 numerical models), the correction factor C_P = 1.02557 and Eq. 4.4 would be as following:

$$\phi = 1.672 \cdot P_m \left(2.718^{-2.5\sqrt{0.0566 + 1.02557 V_P^2}}\right) \quad (4.5)$$

Based on the available test data points [41] in addition to the analysis results obtained from web crippling finite element models, the professional factor P_m and coefficient of variation V_P were determined using the ratio of P_t/P_{ECP*} or P_t/P_{NAS*}. Where P_{ECP*} and P_{NAS*} are the web crippling strengths predicted by ECP and NAS specifications respectively using the new proposed coefficients.

Based on the statistical analysis using the ratio of Pt/P_{ECP*}, the professional factor P_m = 1.085 and coefficient of variation V_P = 0.096. Substituting in Eq. 4.5 for the values of Pm and V_P, the new proposed resistance factor for ECP is ϕ = 0.95.

Based on the statistical analysis using the ratio of P_t/P_{NAS*}, the professional factor Pm = 1.077 and coefficient of variation V_P = 0.087. Substituting in Eq. 4.5 for the values of Pm and V_P, the new proposed resistance factor for NAS is ϕ = 0.95.

Table 4.18 Original and modified resistance factors for ECP&NAS specification

	Original resistance factor		Proposed resistance factor	
	ECP	NAS	ECP	NAS
Reliability index, β	2.50	2.50	2.50	2.50
Resistance factor, ϕ	0.75	0.85	0.95	0.95

The web crippling strengths predicted by the ECP using the current coefficients are compared with the design strengths predicted using the proposed coefficients in Figure 4.41. The comparison shows better prediction for web crippling strengths using the new proposed coefficients. The conservative percentage when using the proposed coefficients increased from 4% to 73%. The load ratio of the finite element strength to the design strength (P_{EF}/P_n) ranges from 0.93 to 1.34 with a mean value of 1.085.

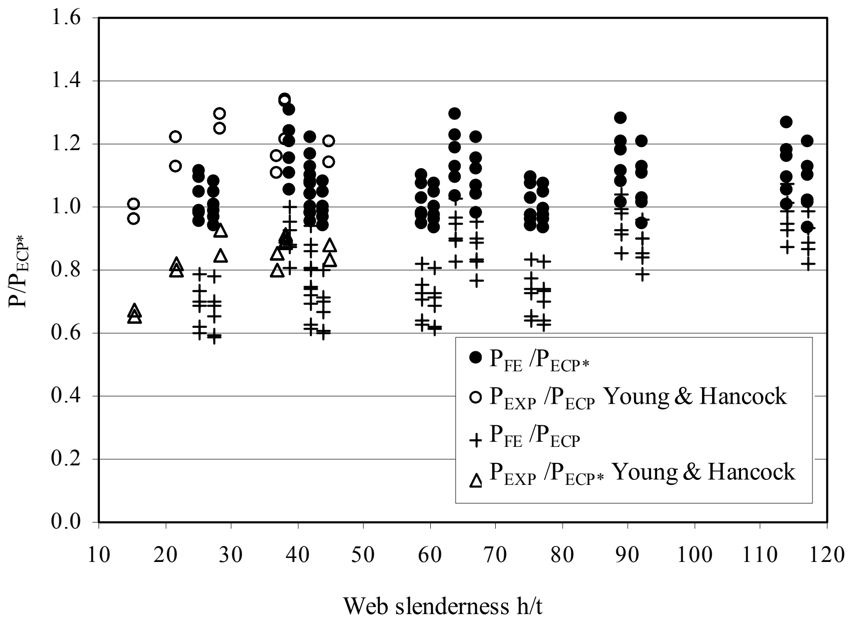

Fig. 4.41 Finite element strength versus original and updated design strength of ECP

The web crippling design strengths calculated using the NAS specification with both original and new proposed coefficients were compared in Figure 4.42. The vertical axis represents the load ratio of the finite element strength to nominal design strength calculated using NAS Specification (P_{EF}/P_n). It was observed that, the new coefficients resulted in improving the predicted web crippling strength. The NAS specification with the proposed coefficients are conservative for about 80% of the data points with load ratio ranges from 0.90 to 1.27 with a mean value of 1.077.

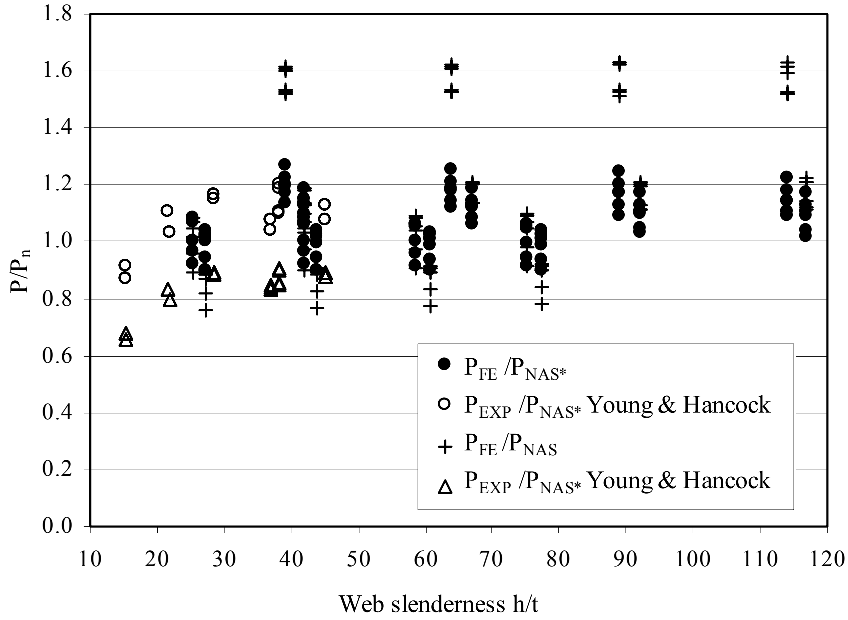

Fig. 4.42 Finite element strength versus original and updated design strength of NAS

4.6 Analysis Results for Combined Bending and Web Crippling Models

Tables 4.19 to 4.24 presented the analysis results of combined bending and web crippling finite element models. In tables, three values of finite element loads were presented with their corresponding bending moments for each modeled channel. The first value $P_{C\text{-}FE}$ was obtained from pure web crippling model while the other two values were obtained from interaction models for spans 1000 and 2000 mm respectively. The corresponding moments $M_{C\text{-}FE}$ were simply calculated as the load times the span divided by 4.

Table 4.19 Finite Element Results of Combined Bending and Web Crippling for Series S5

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	P_{FE} kN	M_{FE} kN.m	$P_{C\text{-}FE}$ kN	$M_{C\text{-}FE}$ kN.m	$P_{C\text{-}FE}$ kN	$M_{C\text{-}FE}$ kN.m
S5-C100×50×2-R6-N25	10.45	1.08	8.05	2.01	5.80	2.90
S5-C100×50×2-R6-N50	12.24	1.35	9.68	2.42	6.65	3.32
S5-C100×50×2-R6-N75	13.62	1.58	10.82	2.71	6.84	3.42
S5-C150×50×2-R6-N25	10.26	1.45	10.43	2.61	7.72	3.86
S5-C150×50×2-R6-N50	12.02	1.77	11.46	2.87	8.62	4.31
S5-C150×50×2-R6-N75	13.37	2.06	12.43	3.11	9.67	4.84
S5-C200×50×2-R6-N25	10.10	1.81	11.01	2.75	8.98	4.49
S5-C200×50×2-R6-N50	11.83	2.19	12.02	3.00	9.88	4.94
S5-C200×50×2-R6-N75	13.16	2.52	13.00	3.25	10.59	5.30
S5-C250×50×2-R6-N25	9.96	2.15	11.30	2.82	9.85	4.92
S5-C250×50×2-R6-N50	11.67	2.60	12.38	3.10	10.74	5.37
S5-C250×50×2-R6-N75	12.99	2.97	13.22	3.31	11.49	5.74

Table 4.20 Finite Element Results of Combined Bending and Web Crippling for Series S6

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	P_{FE} kN	M_{FE} kN.m	$P_{C\text{-}FE}$ kN	$M_{C\text{-}FE}$ kN.m	$P_{C\text{-}FE}$ kN	$M_{C\text{-}FE}$ kN.m
S6-C100×50×3-R6-N25	21.34	2.21	17.07	4.27	10.07	5.03
S6-C100×50×3-R6-N50	25.17	2.77	17.35	4.34	12.96	6.48
S6-C100×50×3-R6-N75	28.92	3.36	22.34	5.58	13.01	6.50
S6-C150×50×3-R6-N25	21.33	3.01	20.17	5.04	16.44	8.22
S6-C150×50×3-R6-N50	25.12	3.71	22.47	5.62	17.36	8.68
S6-C150×50×3-R6-N75	28.76	4.42	24.88	6.22	17.08	8.54
S6-C200×50×3-R6-N25	21.18	3.79	21.29	5.32	17.54	8.77
S6-C200×50×3-R6-N50	24.96	4.62	24.25	6.06	19.42	9.71
S6-C200×50×3-R6-N75	28.45	5.44	26.16	6.54	19.89	9.94
S6-C250×50×3-R6-N25	21.16	4.58	22.35	5.59	19.34	9.67
S6-C250×50×3-R6-N50	24.92	5.55	25.30	6.33	21.34	10.67
S6-C250×50×3-R6-N75	28.38	6.49	27.15	6.79	23.11	11.55

Table 4.21 Finite Element Results of Combined Bending and Web Crippling for Series S7

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	P_{FE} kN	M_{FE} kN.m	P_{C-FE} kN	M_{C-FE} kN.m	P_{C-FE} kN	M_{C-FE} kN.m
S7-C100×50×2-R9-N25	12.04	1.25	7.62	1.90	5.36	2.68
S7-C100×50×2-R9-N50	12.98	1.43	8.73	2.18	6.10	3.05
S7-C100×50×2-R9-N75	13.81	1.61	9.78	2.44	6.33	3.16
S7-C150×50×2-R9-N25	11.51	1.63	10.11	2.53	7.38	3.69
S7-C150×50×2-R9-N50	12.67	1.87	11.39	2.85	8.03	4.01
S7-C150×50×2-R9-N75	13.62	2.09	11.95	2.99	8.74	4.37
S7-C200×50×2-R9-N25	11.33	2.03	10.77	2.69	8.95	4.47
S7-C200×50×2-R9-N50	12.49	2.31	11.99	3.00	9.85	4.93
S7-C200×50×2-R9-N75	13.26	2.54	12.63	3.16	10.41	5.20
S7-C250×50×2-R9-N25	11.03	2.39	10.83	2.71	9.65	4.82
S7-C250×50×2-R9-N50	12.25	2.73	12.08	3.02	11.49	5.74
S7-C250×50×2-R9-N75	13.20	3.02	12.66	3.17	10.98	5.49

Table 4.22 Finite Element Results of Combined Bending and Web Crippling for Series S8

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	P_{FE} kN	M_{FE} kN.m	P_{C-FE} kN	M_{C-FE} kN.m	P_{C-FE} kN	M_{C-FE} kN.m
S8-C100×50×3-R9-N25	20.45	2.12	15.20	3.80	11.34	5.67
S8-C100×50×3-R9-N50	24.14	2.66	17.35	4.34	12.13	6.07
S8-C100×50×3-R9-N75	27.22	3.16	17.91	4.48	10.70	5.35
S8-C150×50×3-R9-N25	20.44	2.89	19.08	4.77	13.75	6.88
S8-C150×50×3-R9-N50	24.14	3.56	21.16	5.29	18.44	9.22
S8-C150×50×3-R9-N75	27.20	4.18	18.64	4.66	18.64	9.32
S8-C200×50×3-R9-N25	20.34	3.64	20.41	5.10	16.71	8.36
S8-C200×50×3-R9-N50	23.84	4.41	23.73	5.93	21.19	10.60
S8-C200×50×3-R9-N75	27.11	5.18	25.38	6.35	19.05	9.53
S8-C250×50×3-R9-N25	20.24	4.38	21.44	5.36	18.68	9.34
S8-C250×50×3-R9-N50	23.61	5.25	24.48	6.12	20.56	10.28
S8-C250×50×3-R9-N75	26.94	6.16	26.02	6.50	21.79	10.90

Figure 4.43 through 4.46 represent samples of von misses stress distribution for different interaction bending and web crippling models at the ultimate load. It was observed in all models with channel depths greater than 100 mm and having 1000 mm span length that, yielding first occurs at the top web- flange intersection along the bearing load length. On the

other hand, for most models having 2000 mm span length, yielding first occurs at the bottom web- flange intersection due to lateral buckling of bottom flanges as shown in Figs 4.51-4.54.

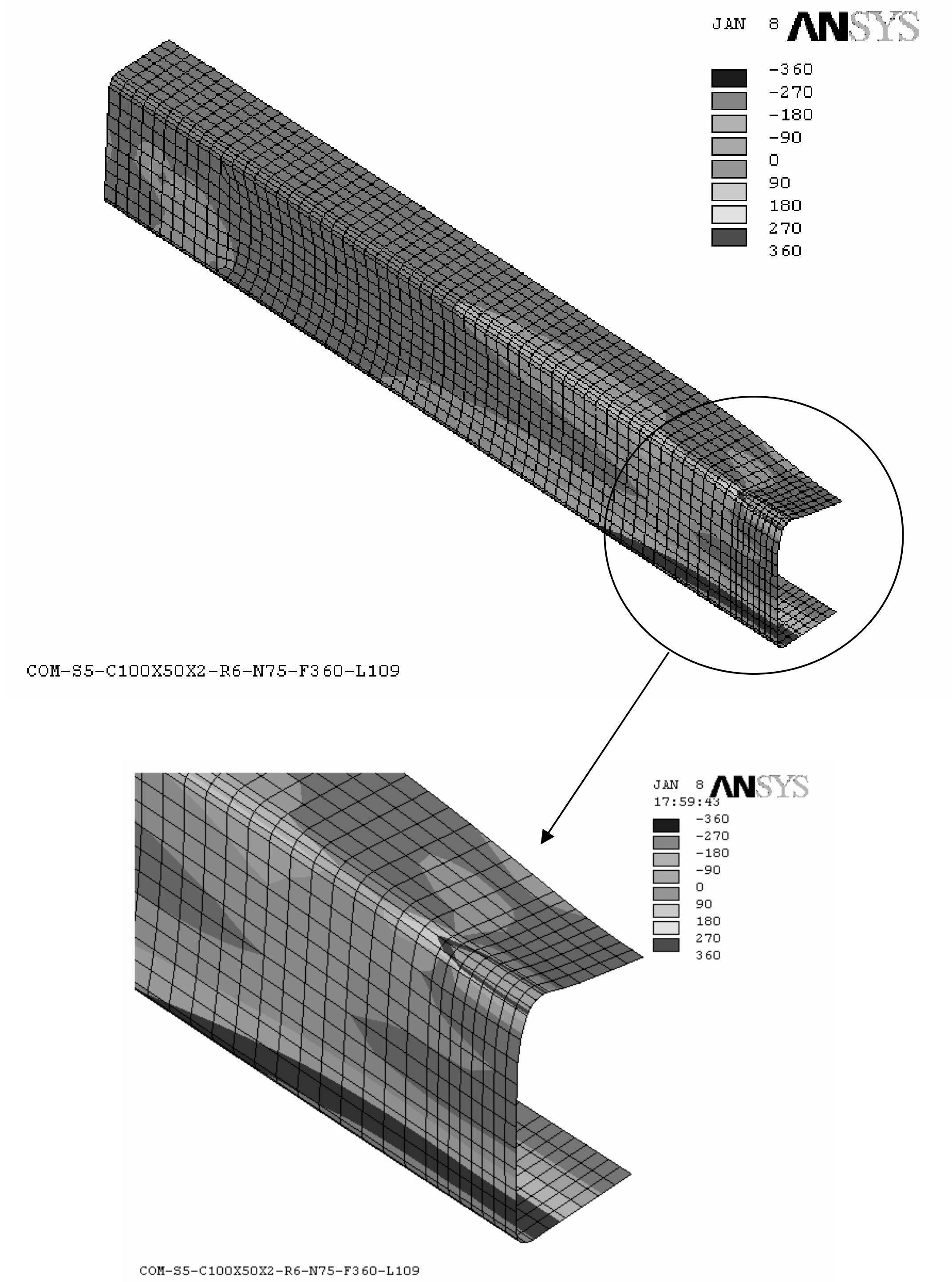

Fig. 4.43 Von Mises stress of model S5-C100×50×2-R6-N75-F360-L109

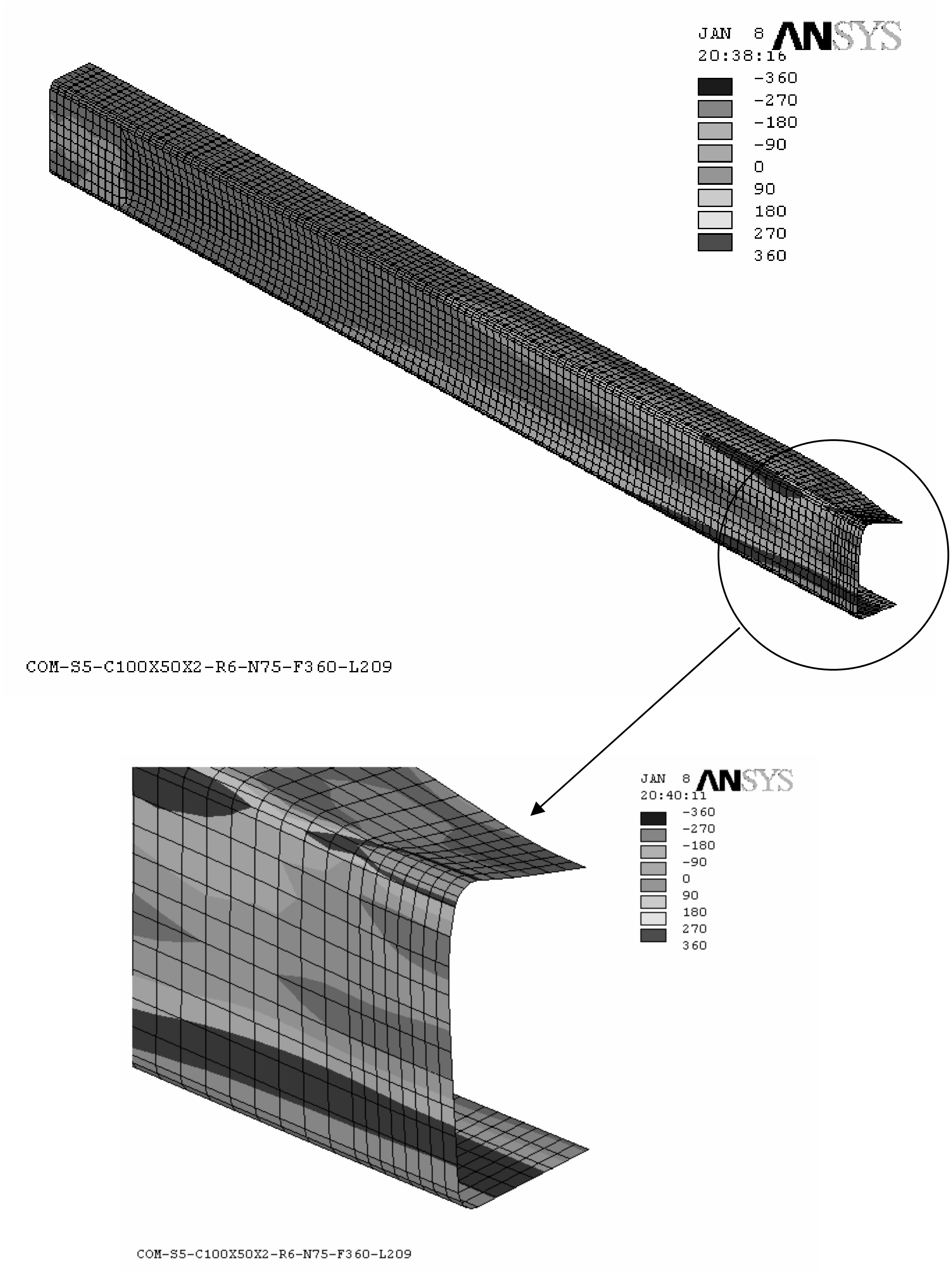

Fig. 4.44 Von Mises stress of model S5-C100×50×2-R6-N75-F360-L209

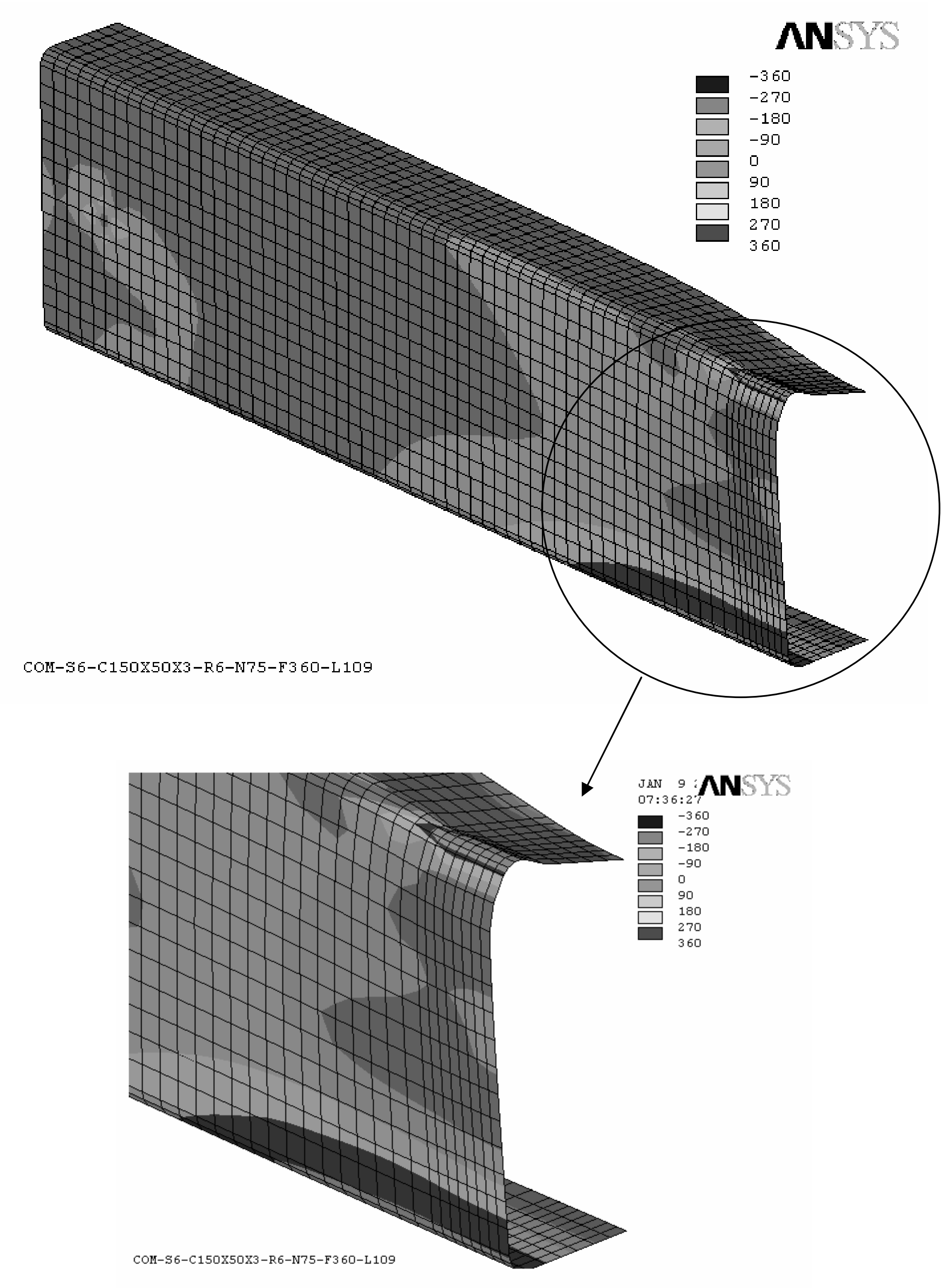

Fig. 4.45 Von Mises stress of model S6-C150×50×3-R6-N75-F360-L109

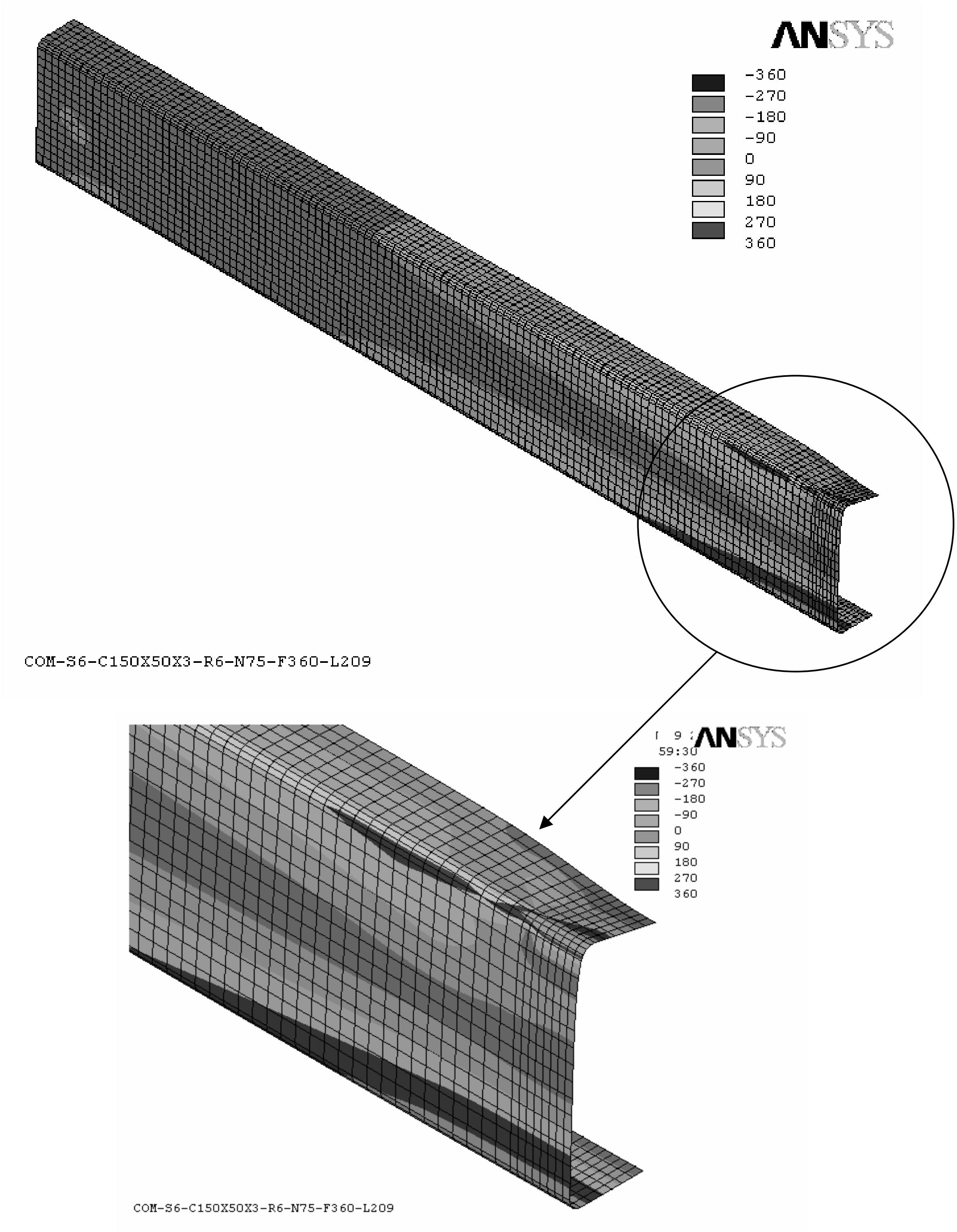

Fig. 4.46 Von Mises stress of model S6-C150×50×3-R6-N75-F360-L209

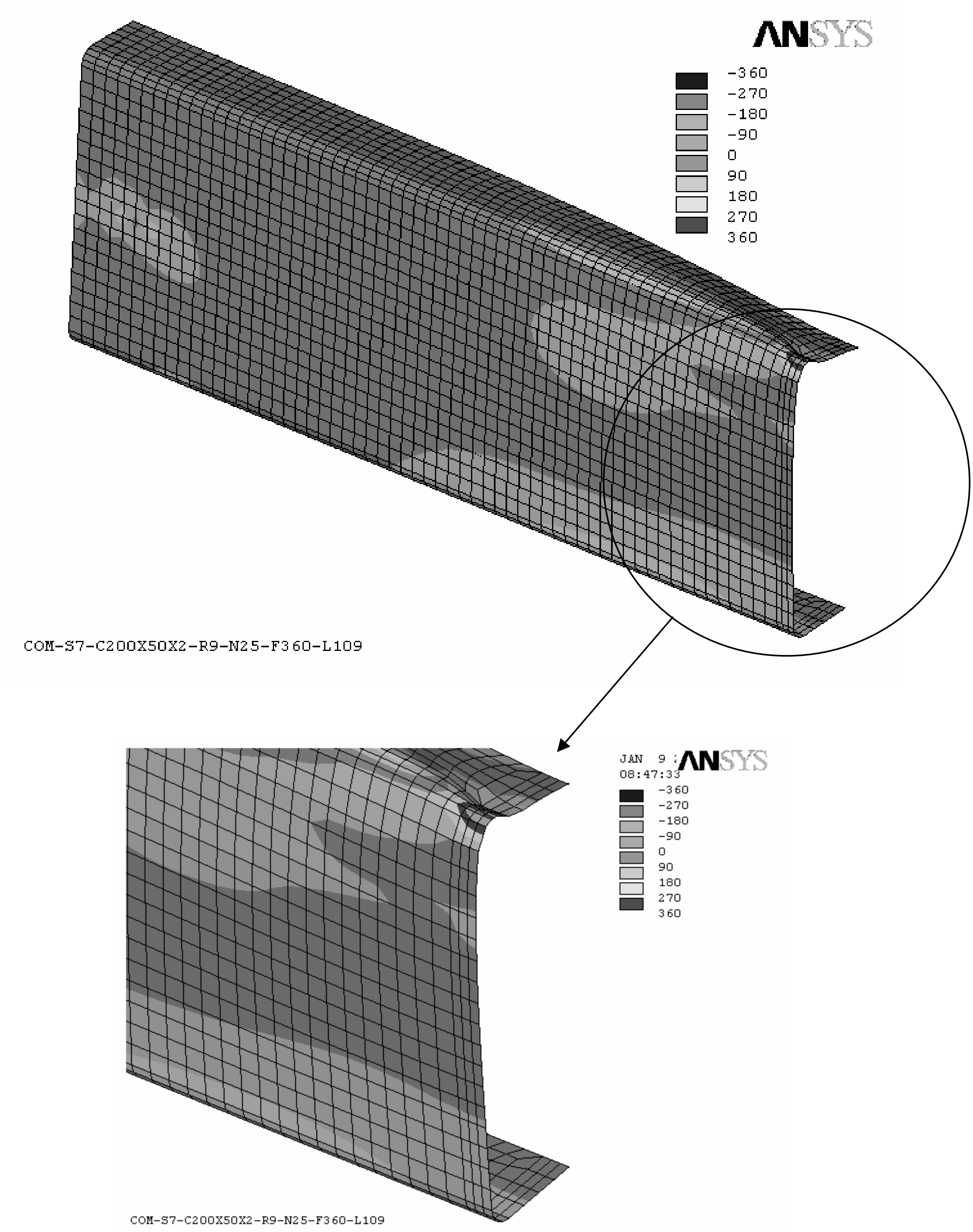

Fig. 4.47 Von Mises stress of model S7-C200×50×2-R9-N25-F360-L109

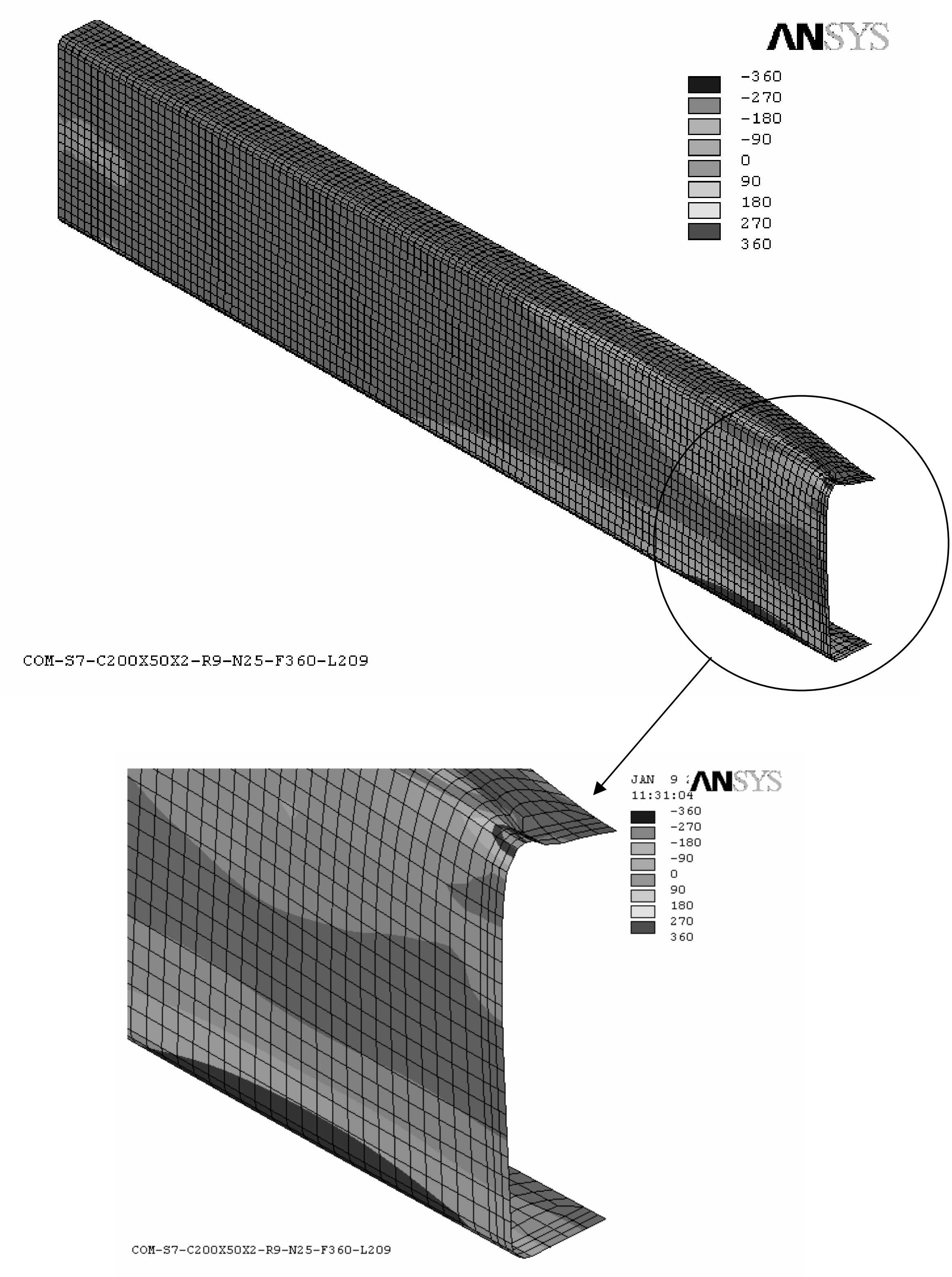

Fig. 4.48 Von Mises stress of model S7-C200×50×2-R9-N25-F360-L209

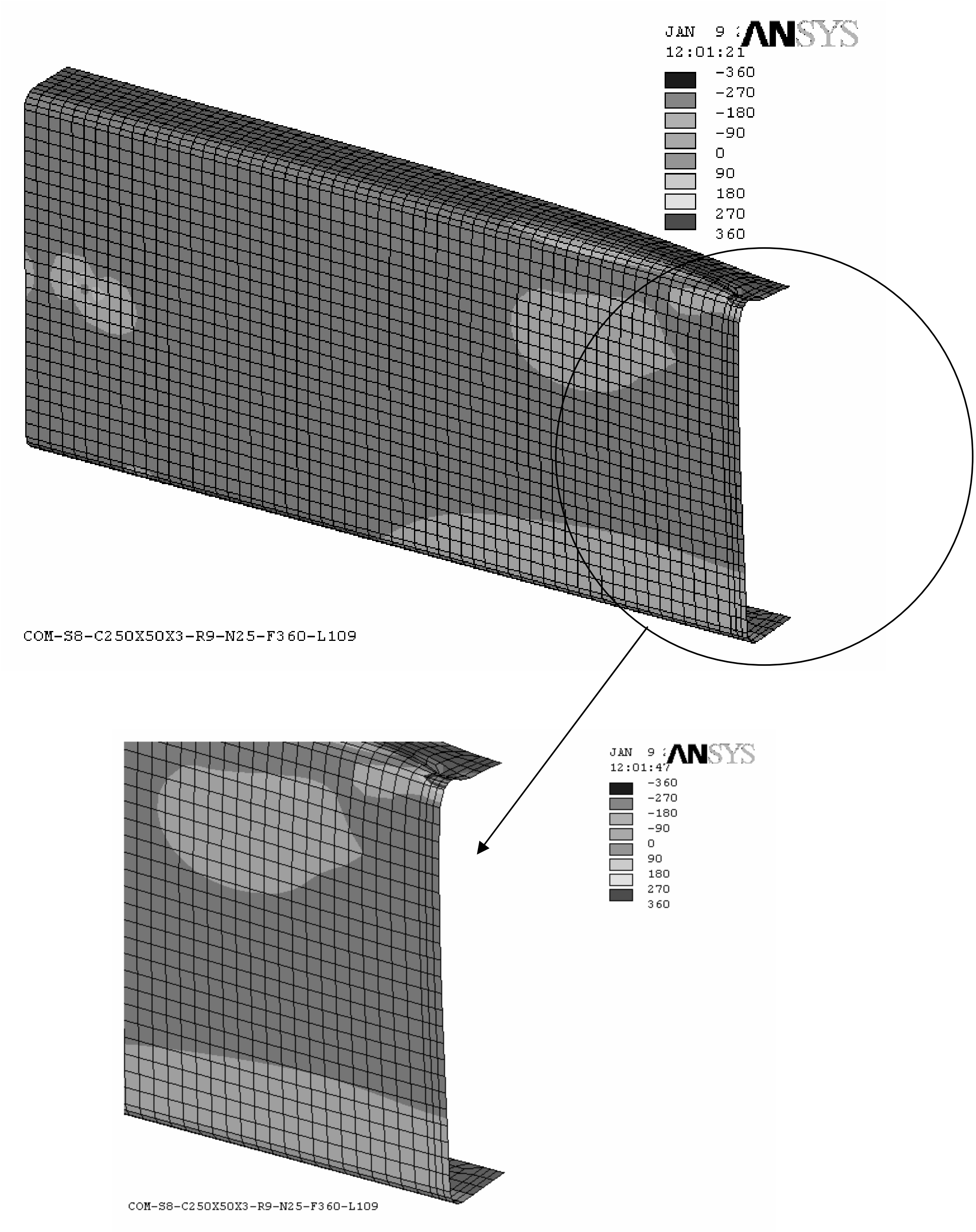

Fig. 4.49 Von Mises stress of model S8-C250×50×3-R9-N25-F360-L109

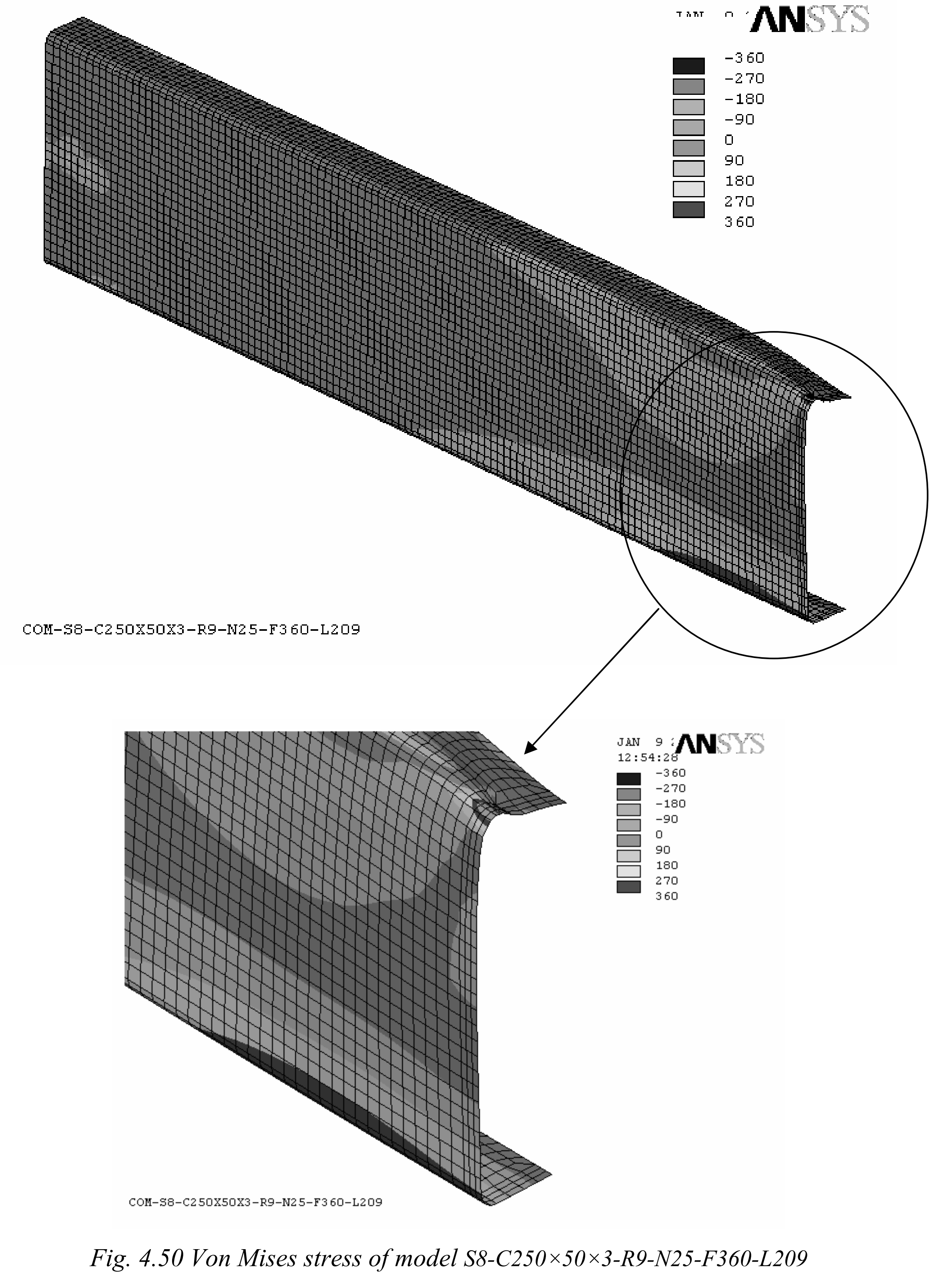

Fig. 4.50 Von Mises stress of model S8-C250×50×3-R9-N25-F360-L209

(a) Span length =1000 mm *(b) Span length =2000 mm*

Fig. 4.51 Failure mode for interaction models "S5-C200×50×3-R6-N75-F360"

(a) Span length =1000 mm *(b) Span length =2000 mm*

Fig. 4.52 Failure mode for interaction models "S6-C150×50×3-R6-N75-F360"

(a) Span length =1000 mm *(b) Span length =2000 mm*

Fig. 4.53 Failure mode for interaction models "S8-C250×50×3-R9-N25-F360"

(a) Span length =1000 mm *(b) Span length =2000 mm*

Fig. 4.54 Failure mode for interaction models "S7-C200×50×2-R9-N25-F360"

Figure 4.55 through 4.58 present samples of load versus web deformation for different interaction bending and web crippling models. It was observed in some models that, an increase in the load capacity occurred after the ultimate load due to strain hardening see Figs 4.57 and 4.58.

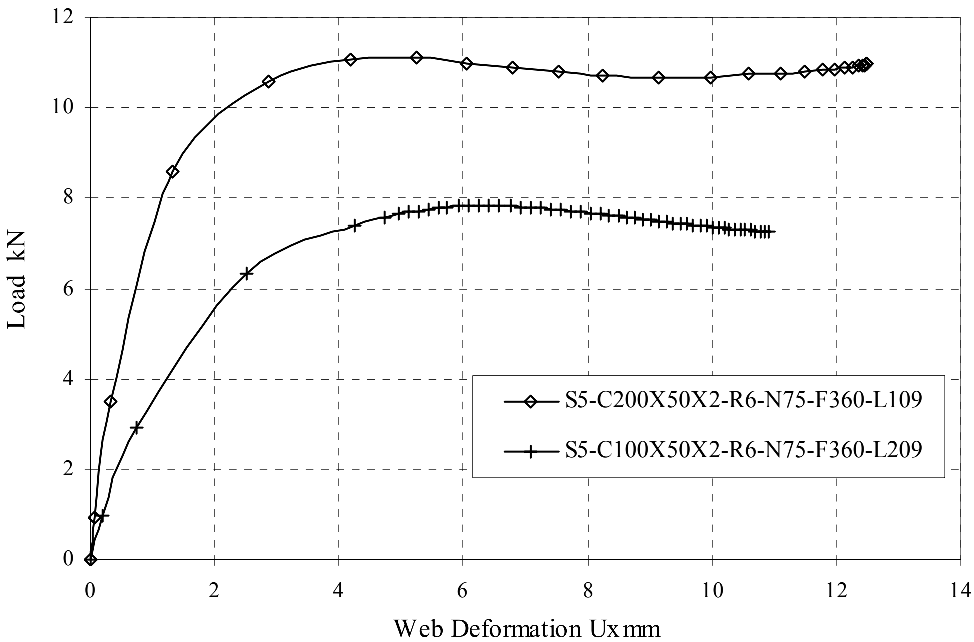

Fig. 4.55 Load versus web deformation of interaction models "S5-C200×50×2-R6-N75-F360"

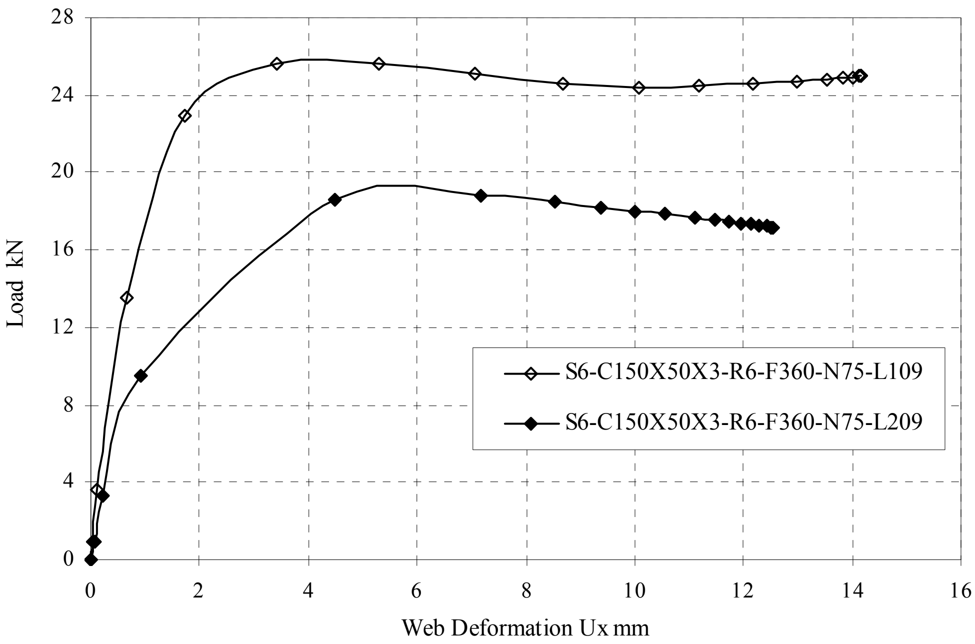

Fig. 4.56 Load versus web deformation of interaction models "S6-C150×50×3-R6-N75-F360"

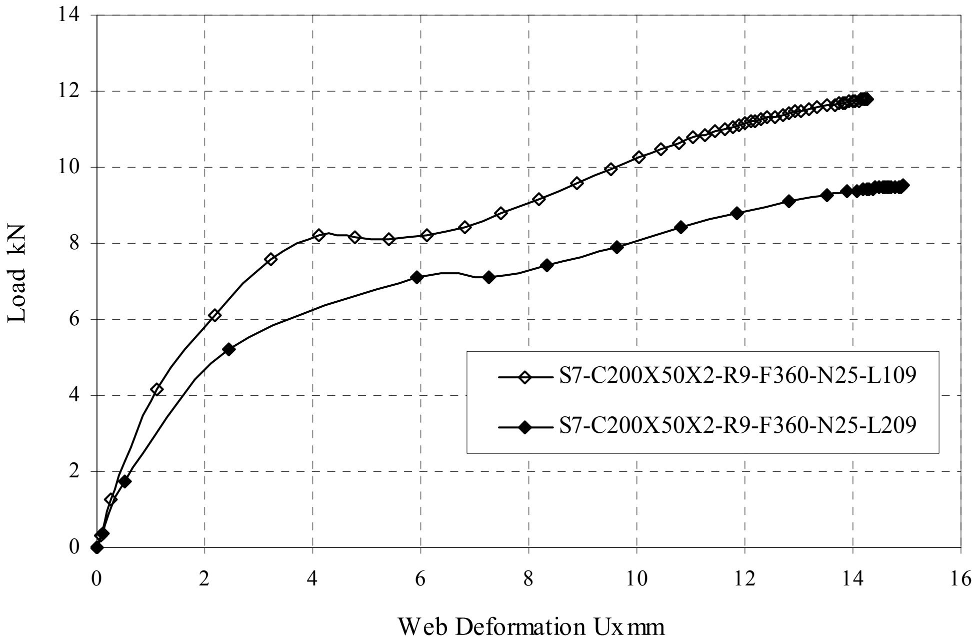

Fig. 4.57 Load versus web deformation of interaction models "S7-C200×50×2-R9-N25-F360"

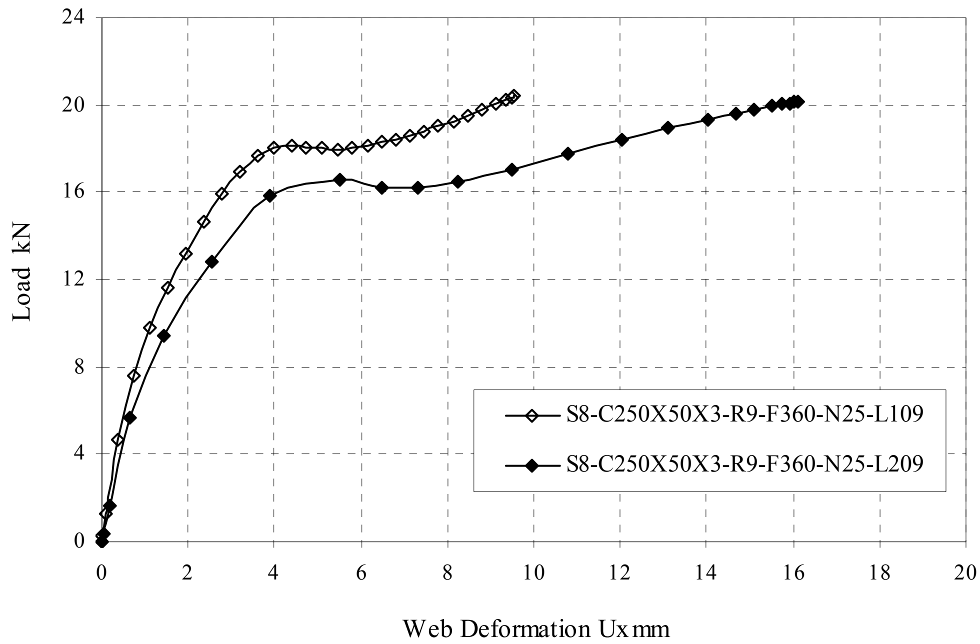

Fig. 4.58 Load versus web deformation of interaction models "S8-C250×50×3-R9-N25-F360"

4.7 Finite Element Interaction Strengths versus Design Codes

The interaction finite element strengths were compared with the interaction design equations specified in AS/NZS, BS, ECP and NAS. The interaction design equations required calculating both the web crippling strengths and the flexural bending strengths. The web crippling strengths were individually calculated according to each specification. On the other side, the flexural bending strength calculations of AS/NZS, ECP and NAS specifications were similar, based on the effective section modulus multiplied by the design yield strength. The only difference in calculating the flexural bending strengths according to BS standard was using different values for the design yield strength, see the definitions of Eq.2.34. Therefore, the nominal bending strengths "M_n" calculated according to NAS specification were used to express the nominal bending strengths for both AS/NZS and ECP specifications. On the other hand, different values for the nominal bending strengths "M_C" were calculated according to BS standard.

Table 4.24 through 4.27 represent the web crippling strengths and the nominal bending strengths calculated according to the four codes (AS/NZS, BS, ECP and NAS). The original web crippling strengths for both ECP and NAS specifications were replaced with the modified strengths.

Table 4.24 Nominal bending "M_n or M_C" and web crippling strengths "P_n or P_W" for Series "S5" according to (AS/NZS, BS, ECP and NAS)

Specimen label	Web d mm	Flange b mm	Thick. t mm	Radius R mm	AS/NZS		BS-5950		ECP		NAS	
					P_n kN	M_n kN.m	P_W kN	M_C kN.m	P_n* kN	M_n kN.m	P_n* kN	M_n kN.m
S5-C100×50×2-R6-N25-F360	100	50	2	6	18.36	3.34	16.46	3.34	10.24	3.34	10.53	3.34
S5-C100×50×2-R6-N50-F360	100	50	2	6	19.84	3.34	17.78	3.34	12.29	3.34	12.05	3.34
S5-C100×50×2-R6-N75-F360	100	50	2	6	21.31	3.34	19.10	3.34	14.34	3.34	13.21	3.34
S5-C150×50×2-R6-N25-F360	150	50	2	6	17.69	6.02	15.85	5.93	10.23	6.02	10.52	6.02
S5-C150×50×2-R6-N50-F360	150	50	2	6	19.11	6.02	17.12	5.93	12.28	6.02	12.03	6.02
S5-C150×50×2-R6-N75-F360	150	50	2	6	20.53	6.02	18.40	5.93	14.33	6.02	13.18	6.02
S5-C200×50×2-R6-N25-F360	200	50	2	6	17.02	9.30	15.24	8.67	10.22	9.30	10.50	9.30
S5-C200×50×2-R6-N50-F360	200	50	2	6	18.39	9.30	16.47	8.67	12.27	9.30	12.01	9.30
S5-C200×50×2-R6-N75-F360	200	50	2	6	19.76	9.30	17.70	8.67	14.31	9.30	13.16	9.30
S5-C250×50×2-R6-N25-F360	250	50	2	6	16.35	13.20	14.64	11.59	10.21	13.20	10.49	13.20
S5-C250×50×2-R6-N50-F360	250	50	2	6	17.66	13.20	15.81	11.59	12.26	13.20	11.99	13.20
S5-C250×50×2-R6-N75-F360	250	50	2	6	18.98	13.20	16.99	11.59	14.30	13.20	13.15	13.20

** Indication for using the new proposed web crippling coefficients.*

Table 4.25 Nominal bending "M_n or M_C" and web crippling strengths "P_n or P_W" for Series "S6" according to (AS/NZS, BS, ECP and NAS)

Specimen label	Web d mm	Flange b mm	Thick. t mm	Radius R mm	AS/NZS		BS-5950		ECP		NAS	
					P_n kN	M_n kN.m	P_W kN	M_C kN.m	P_n* kN	M_n kN.m	P_n* kN	M_n kN.m
S6-C100×50×3-R6-N25-F360	100	50	3	6	43.86	5.64	39.44	5.64	22.72	5.64	23.65	5.64
S6-C100×50×3-R6-N50-F360	100	50	3	6	46.28	5.64	41.61	5.64	25.97	5.64	26.61	5.64
S6-C100×50×3-R6-N75-F360	100	50	3	6	48.69	5.64	43.78	5.64	29.21	5.64	28.89	5.64
S6-C150×50×3-R6-N25-F360	150	50	3	6	42.81	9.97	38.49	9.97	22.71	9.97	23.62	9.97
S6-C150×50×3-R6-N50-F360	150	50	3	6	45.17	9.97	40.61	9.97	25.95	9.97	26.58	9.97
S6-C150×50×3-R6-N75-F360	150	50	3	6	47.53	9.97	42.73	9.97	29.19	9.97	28.84	9.97
S6-C200×50×3-R6-N25-F360	200	50	3	6	41.77	15.22	37.54	15.21	22.69	15.22	23.59	15.22
S6-C200×50×3-R6-N50-F360	200	50	3	6	44.07	15.22	39.61	15.21	25.93	15.22	26.54	15.22
S6-C200×50×3-R6-N75-F360	200	50	3	6	46.37	15.22	41.68	15.21	29.18	15.22	28.81	15.22
S6-C250×50×3-R6-N25-F360	250	50	3	6	40.72	21.36	36.60	20.58	22.68	21.36	23.57	21.36
S6-C250×50×3-R6-N50-F360	250	50	3	6	42.97	21.36	38.62	20.58	25.92	21.36	26.52	21.36
S6-C250×50×3-R6-N75-F360	250	50	3	6	45.21	21.36	40.63	20.58	29.16	21.36	28.78	21.36

** Indication for using the new proposed web crippling coefficients.*

Table 4.26 Nominal bending "M_n or M_C" and web crippling strengths "P_n or P_W" for Series "S7" according to (AS/NZS, BS, ECP and NAS)

Specimen label	Web d mm	Flange b mm	Thick. t mm	Radius R mm	AS/NZS		BS-5950		ECP		NAS	
					P_n kN	M_n kN.m	P_W kN	M_C kN.m	P_n* kN	M_n kN.m	P_n* kN	M_n kN.m
S7-C100×50×2-R9-N25-F360	100	50	2	9	16.55	3.39	14.77	3.39	9.39	3.39	9.71	3.39
S7-C100×50×2-R9-N50-F360	100	50	2	9	17.88	3.39	15.96	3.39	11.27	3.39	11.10	3.39
S7-C100×50×2-R9-N75-F360	100	50	2	9	19.22	3.39	17.15	3.39	13.15	3.39	12.17	3.39
S7-C150×50×2-R9-N25-F360	150	50	2	9	15.95	6.09	14.23	6.04	9.38	6.09	9.69	6.09
S7-C150×50×2-R9-N50-F360	150	50	2	9	17.23	6.09	15.37	6.04	11.26	6.09	11.08	6.09
S7-C150×50×2-R9-N75-F360	150	50	2	9	18.52	6.09	16.52	6.04	13.14	6.09	12.15	6.09
S7-C200×50×2-R9-N25-F360	200	50	2	9	15.35	9.30	13.68	8.73	9.37	9.30	9.67	9.30
S7-C200×50×2-R9-N50-F360	200	50	2	9	16.59	9.30	14.79	8.73	11.25	9.30	11.06	9.30
S7-C200×50×2-R9-N75-F360	200	50	2	9	17.82	9.30	15.89	8.73	13.12	9.30	12.13	9.30
S7-C250×50×2-R9-N25-F360	250	50	2	9	14.75	13.32	13.14	11.78	9.36	13.32	9.66	13.32
S7-C250×50×2-R9-N50-F360	250	50	2	9	15.94	13.32	14.20	11.78	11.24	13.32	11.05	13.32
S7-C250×50×2-R9-N75-F360	250	50	2	9	17.12	13.32	15.25	11.78	13.11	13.32	12.11	13.32

** Indication for using the new proposed web crippling coefficients.*

Table 4.27 Nominal bending "M_n or M_C" and web crippling strengths "P_n or P_W" for Series "S8" according to (AS/NZS, BS, ECP and NAS)

Specimen label	Web d mm	Flange b mm	Thick. t mm	Radius R mm	AS/NZS		BS-5950		ECP		NAS	
					P_n kN	M_n kN.m	P_W kN	M_C kN.m	P_n* kN	M_n kN.m	P_n* kN	M_n kN.m
S8-C100×50×3-R9-N25-F360	100	50	3	9	41.18	5.68	36.92	5.68	21.53	5.68	22.23	5.68
S8-C100×50×3-R9-N50-F360	100	50	3	9	43.45	5.68	38.95	5.68	24.60	5.68	25.01	5.68
S8-C100×50×3-R9-N75-F360	100	50	3	9	45.72	5.68	40.99	5.68	27.68	5.68	27.14	5.68
S8-C150×50×3-R9-N25-F360	150	50	3	9	40.20	10.02	36.03	10.02	21.51	10.02	22.19	10.02
S8-C150×50×3-R9-N50-F360	150	50	3	9	42.41	10.02	38.02	10.02	24.59	10.02	24.97	10.02
S8-C150×50×3-R9-N75-F360	150	50	3	9	44.63	10.02	40.01	10.02	27.66	10.02	27.10	10.02
S8-C200×50×3-R9-N25-F360	200	50	3	9	39.22	15.28	35.15	15.28	21.50	15.28	22.17	15.28
S8-C200×50×3-R9-N50-F360	200	50	3	9	41.38	15.28	37.08	15.28	24.57	15.28	24.94	15.28
S8-C200×50×3-R9-N75-F360	200	50	3	9	43.54	15.28	39.02	15.28	27.64	15.28	27.07	15.28
S8-C250×50×3-R9-N25-F360	250	50	3	9	38.24	21.44	34.26	20.75	21.49	21.44	22.14	21.44
S8-C250×50×3-R9-N50-F360	250	50	3	9	40.35	21.44	36.15	20.75	24.55	21.44	24.92	21.44
S8-C250×50×3-R9-N75-F360	250	50	3	9	42.46	21.44	38.04	20.75	27.62	21.44	27.04	21.44

** Indication for using the new proposed web crippling coefficients.*

Tables 4.28 to 4.31 represented the ratios of the finite element load to the predicted web crippling strengths using AS/NZS standard (P/P_n) and their corresponding moment ratios (M/M_n). Figure 4.59 showed that the interaction equation for bending and web crippling of AS/NZS was generally un-conservative.

Table 4.28 Finite element load to AS/NZS nominal web crippling ratios and corresponding moment ratios of series"S5"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$
S5-C100×50×2-R6-N25	0.57	0.32	0.44	0.60	0.32	0.87
S5-C100×50×2-R6-N50	0.62	0.40	0.49	0.72	0.34	1.00
S5-C100×50×2-R6-N75	0.64	0.47	0.51	0.81	0.32	1.02
S5-C150×50×2-R6-N25	0.58	0.24	0.59	0.43	0.44	0.64
S5-C150×50×2-R6-N50	0.63	0.29	0.60	0.48	0.45	0.72
S5-C150×50×2-R6-N75	0.65	0.34	0.61	0.52	0.47	0.80
S5-C200×50×2-R6-N25	0.59	0.19	0.65	0.30	0.53	0.48
S5-C200×50×2-R6-N50	0.64	0.24	0.65	0.32	0.54	0.53
S5-C200×50×2-R6-N75	0.67	0.27	0.66	0.35	0.54	0.57
S5-C250×50×2-R6-N25	0.61	0.16	0.69	0.21	0.60	0.37
S5-C250×50×2-R6-N50	0.66	0.20	0.70	0.23	0.61	0.41
S5-C250×50×2-R6-N75	0.68	0.23	0.70	0.25	0.61	0.44

Table 4.29 Finite element load to AS/NZS nominal web crippling ratios and corresponding moment ratios of series"S6"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$
S6-C100×50×3-R6-N25	0.48	0.39	0.39	0.76	0.23	0.89
S6-C100×50×3-R6-N50	0.54	0.49	0.37	0.77	0.28	1.15
S6-C100×50×3-R6-N75	0.59	0.60	0.46	0.99	0.27	1.15
S6-C150×50×3-R6-N25	0.50	0.30	0.47	0.51	0.38	0.82
S6-C150×50×3-R6-N50	0.55	0.37	0.50	0.56	0.38	0.87
S6-C150×50×3-R6-N75	0.60	0.44	0.52	0.62	0.36	0.86
S6-C200×50×3-R6-N25	0.50	0.25	0.51	0.35	0.42	0.58
S6-C200×50×3-R6-N50	0.56	0.30	0.55	0.40	0.44	0.64
S6-C200×50×3-R6-N75	0.61	0.36	0.56	0.43	0.43	0.65
S6-C250×50×3-R6-N25	0.52	0.21	0.55	0.26	0.47	0.45
S6-C250×50×3-R6-N50	0.58	0.26	0.59	0.30	0.50	0.50
S6-C250×50×3-R6-N75	0.62	0.30	0.60	0.32	0.51	0.54

Table 4.30 Finite element load to AS/NZS nominal web crippling ratios and corresponding moment ratios of series"S7"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$
S7-C100×50×2-R9-N25	0.72	0.37	0.46	0.56	0.32	0.79
S7-C100×50×2-R9-N50	0.72	0.42	0.49	0.64	0.34	0.90
S7-C100×50×2-R9-N75	0.71	0.47	0.51	0.72	0.33	0.93
S7-C150×50×2-R9-N25	0.72	0.27	0.63	0.41	0.46	0.61
S7-C150×50×2-R9-N50	0.73	0.31	0.66	0.47	0.47	0.66
S7-C150×50×2-R9-N75	0.73	0.34	0.65	0.49	0.47	0.72
S7-C200×50×2-R9-N25	0.73	0.22	0.70	0.29	0.58	0.48
S7-C200×50×2-R9-N50	0.75	0.25	0.72	0.32	0.59	0.53
S7-C200×50×2-R9-N75	0.74	0.27	0.71	0.34	0.58	0.56
S7-C250×50×2-R9-N25	0.74	0.18	0.73	0.20	0.65	0.36
S7-C250×50×2-R9-N50	0.76	0.20	0.76	0.23	0.72	0.43
S7-C250×50×2-R9-N75	0.77	0.23	0.74	0.24	0.64	0.41

Table 4.31 Finite element load to AS/NZS nominal web crippling ratios and corresponding moment ratios of series"S8"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$
S8-C100×50×3-R9-N25	0.49	0.37	0.37	0.67	0.28	1.00
S8-C100×50×3-R9-N50	0.55	0.47	0.40	0.76	0.28	1.07
S8-C100×50×3-R9-N75	0.59	0.56	0.39	0.79	0.23	0.94
S8-C150×50×3-R9-N25	0.51	0.29	0.47	0.48	0.34	0.69
S8-C150×50×3-R9-N50	0.57	0.36	0.50	0.53	0.43	0.92
S8-C150×50×3-R9-N75	0.61	0.42	0.42	0.46	0.42	0.93
S8-C200×50×3-R9-N25	0.52	0.24	0.52	0.33	0.43	0.55
S8-C200×50×3-R9-N50	0.57	0.29	0.57	0.39	0.51	0.69
S8-C200×50×3-R9-N75	0.62	0.34	0.58	0.42	0.44	0.62
S8-C250×50×3-R9-N25	0.53	0.20	0.56	0.25	0.49	0.44
S8-C250×50×3-R9-N50	0.58	0.25	0.61	0.29	0.51	0.48
S8-C250×50×3-R9-N75	0.63	0.29	0.61	0.30	0.51	0.51

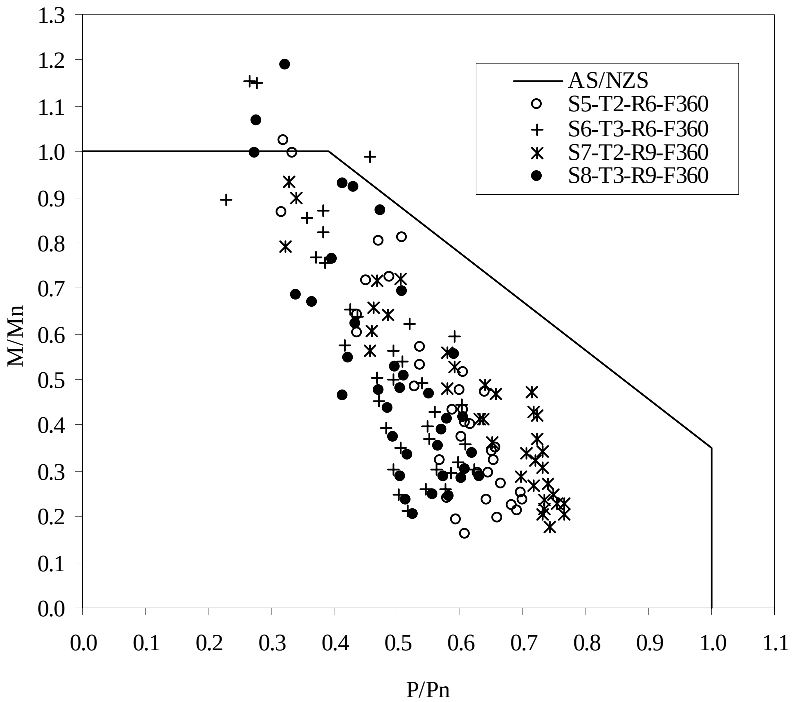

Fig. 4.59 Finite element results versus interaction equation of AS/NZS

Tables 4.32 to 4.35 represented the ratios of the finite element load to the predicted web crippling strengths using BS standard (P/P_W) and their corresponding moment ratios

(M/M_n). Figure 4.60 showed that the interaction equation for bending and web crippling of BS standard was generally un-conservative.

Table 4.32 Finite element load to BS nominal web crippling ratios and corresponding moment ratios of series"S5"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_w}$	$\frac{M}{M_c}$	$\frac{P}{P_w}$	$\frac{M}{M_c}$	$\frac{P}{P_w}$	$\frac{M}{M_c}$
S5-C100×50×2-R6-N25	0.63	0.32	0.49	0.60	0.35	0.87
S5-C100×50×2-R6-N50	0.69	0.40	0.54	0.72	0.37	1.00
S5-C100×50×2-R6-N75	0.71	0.47	0.57	0.81	0.36	1.02
S5-C150×50×2-R6-N25	0.65	0.24	0.66	0.44	0.49	0.65
S5-C150×50×2-R6-N50	0.70	0.30	0.67	0.48	0.50	0.73
S5-C150×50×2-R6-N75	0.73	0.35	0.68	0.52	0.53	0.81
S5-C200×50×2-R6-N25	0.66	0.21	0.72	0.32	0.59	0.52
S5-C200×50×2-R6-N50	0.72	0.25	0.73	0.35	0.60	0.57
S5-C200×50×2-R6-N75	0.74	0.29	0.73	0.38	0.60	0.61
S5-C250×50×2-R6-N25	0.68	0.19	0.77	0.24	0.67	0.42
S5-C250×50×2-R6-N50	0.74	0.22	0.78	0.27	0.68	0.46
S5-C250×50×2-R6-N75	0.76	0.26	0.78	0.29	0.68	0.50

Table 4.33 Finite element load to BS nominal web crippling ratios and corresponding moment ratios of series"S6"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_w}$	$\frac{M}{M_c}$	$\frac{P}{P_w}$	$\frac{M}{M_c}$	$\frac{P}{P_w}$	$\frac{M}{M_c}$
S6-C100×50×3-R6-N25	0.54	0.39	0.43	0.76	0.26	0.89
S6-C100×50×3-R6-N50	0.60	0.49	0.42	0.77	0.31	1.15
S6-C100×50×3-R6-N75	0.66	0.60	0.51	0.99	0.30	1.15
S6-C150×50×3-R6-N25	0.55	0.30	0.52	0.51	0.43	0.82
S6-C150×50×3-R6-N50	0.62	0.37	0.55	0.56	0.43	0.87
S6-C150×50×3-R6-N75	0.67	0.44	0.58	0.62	0.40	0.86
S6-C200×50×3-R6-N25	0.56	0.25	0.57	0.35	0.47	0.58
S6-C200×50×3-R6-N50	0.63	0.30	0.61	0.40	0.49	0.64
S6-C200×50×3-R6-N75	0.68	0.36	0.63	0.43	0.48	0.65
S6-C250×50×3-R6-N25	0.58	0.22	0.61	0.27	0.53	0.47
S6-C250×50×3-R6-N50	0.65	0.27	0.66	0.31	0.55	0.52
S6-C250×50×3-R6-N75	0.70	0.32	0.67	0.33	0.57	0.56

Table 4.34 Finite element load to BS nominal web crippling ratios and corresponding moment ratios of series"S7"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_w}$	$\frac{M}{M_c}$	$\frac{P}{P_w}$	$\frac{M}{M_c}$	$\frac{P}{P_w}$	$\frac{M}{M_c}$
S7-C100×50×2-R9-N25	0.81	0.37	0.52	0.56	0.36	0.79
S7-C100×50×2-R9-N50	0.81	0.42	0.55	0.64	0.38	0.90
S7-C100×50×2-R9-N75	0.81	0.47	0.57	0.72	0.37	0.93
S7-C150×50×2-R9-N25	0.81	0.27	0.71	0.42	0.52	0.61
S7-C150×50×2-R9-N50	0.82	0.31	0.74	0.47	0.52	0.66
S7-C150×50×2-R9-N75	0.82	0.35	0.72	0.49	0.53	0.72
S7-C200×50×2-R9-N25	0.83	0.23	0.79	0.31	0.65	0.51
S7-C200×50×2-R9-N50	0.84	0.26	0.81	0.34	0.67	0.56
S7-C200×50×2-R9-N75	0.83	0.29	0.80	0.36	0.66	0.60
S7-C250×50×2-R9-N25	0.84	0.20	0.82	0.23	0.73	0.41
S7-C250×50×2-R9-N50	0.86	0.23	0.85	0.26	0.81	0.49
S7-C250×50×2-R9-N75	0.87	0.26	0.83	0.27	0.72	0.47

Table 4.35 Finite element load to BS nominal web crippling ratios and corresponding moment ratios of series"S8"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_w}$	$\frac{M}{M_c}$	$\frac{P}{P_w}$	$\frac{M}{M_c}$	$\frac{P}{P_w}$	$\frac{M}{M_c}$
S8-C100×50×3-R9-N25	0.55	0.37	0.41	0.67	0.31	1.00
S8-C100×50×3-R9-N50	0.62	0.47	0.45	0.76	0.31	1.07
S8-C100×50×3-R9-N75	0.66	0.56	0.44	0.79	0.26	0.94
S8-C150×50×3-R9-N25	0.57	0.29	0.53	0.48	0.38	0.69
S8-C150×50×3-R9-N50	0.63	0.36	0.56	0.53	0.49	0.92
S8-C150×50×3-R9-N75	0.68	0.42	0.47	0.46	0.47	0.93
S8-C200×50×3-R9-N25	0.58	0.24	0.58	0.33	0.48	0.55
S8-C200×50×3-R9-N50	0.64	0.29	0.64	0.39	0.57	0.69
S8-C200×50×3-R9-N75	0.69	0.34	0.65	0.42	0.49	0.62
S8-C250×50×3-R9-N25	0.59	0.21	0.63	0.26	0.55	0.45
S8-C250×50×3-R9-N50	0.65	0.25	0.68	0.29	0.57	0.50
S8-C250×50×3-R9-N75	0.71	0.30	0.68	0.31	0.57	0.53

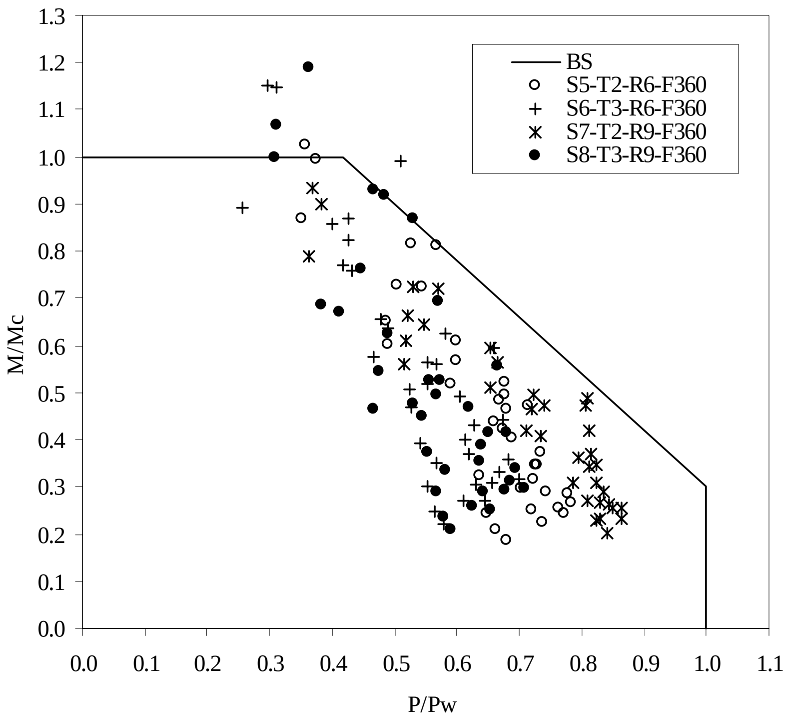

Fig. 4.60 Finite element results versus interaction equation of BS

Tables 4.36 to 4.39 represented the ratios of the finite element load to the predicted web crippling strengths using ECP specification (P/P_n) and their corresponding moment ratios

(M/M_n). Figure 4.61 showed that ECP interaction equation for bending and web crippling was generally conservative.

Table 4.36 Finite element load to ECP nominal web crippling ratios and corresponding moment ratios of series"S5"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$
S5-C100×50×2-R6-N25	0.70	0.32	0.54	0.60	0.39	0.87
S5-C100×50×2-R6-N50	0.81	0.40	0.64	0.72	0.44	1.00
S5-C100×50×2-R6-N75	0.89	0.47	0.71	0.81	0.45	1.02
S5-C150×50×2-R6-N25	0.72	0.24	0.73	0.43	0.54	0.64
S5-C150×50×2-R6-N50	0.83	0.29	0.79	0.48	0.59	0.72
S5-C150×50×2-R6-N75	0.91	0.34	0.84	0.52	0.66	0.80
S5-C200×50×2-R6-N25	0.73	0.19	0.80	0.30	0.65	0.48
S5-C200×50×2-R6-N50	0.85	0.24	0.86	0.32	0.71	0.53
S5-C200×50×2-R6-N75	0.93	0.27	0.92	0.35	0.75	0.57
S5-C250×50×2-R6-N25	0.75	0.16	0.85	0.21	0.74	0.37
S5-C250×50×2-R6-N50	0.87	0.20	0.92	0.23	0.80	0.41
S5-C250×50×2-R6-N75	0.95	0.23	0.97	0.25	0.84	0.44

Table 4.37 Finite element load to ECP nominal web crippling ratios and corresponding moment ratios of series"S6"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$
S6-C100×50×3-R6-N25	0.59	0.39	0.47	0.76	0.28	0.89
S6-C100×50×3-R6-N50	0.69	0.49	0.47	0.77	0.35	1.15
S6-C100×50×3-R6-N75	0.78	0.60	0.60	0.99	0.35	1.15
S6-C150×50×3-R6-N25	0.60	0.30	0.57	0.51	0.46	0.82
S6-C150×50×3-R6-N50	0.70	0.37	0.63	0.56	0.49	0.87
S6-C150×50×3-R6-N75	0.80	0.44	0.69	0.62	0.47	0.86
S6-C200×50×3-R6-N25	0.61	0.25	0.62	0.35	0.51	0.58
S6-C200×50×3-R6-N50	0.72	0.30	0.70	0.40	0.56	0.64
S6-C200×50×3-R6-N75	0.81	0.36	0.74	0.43	0.56	0.65
S6-C250×50×3-R6-N25	0.63	0.21	0.66	0.26	0.57	0.45
S6-C250×50×3-R6-N50	0.73	0.26	0.74	0.30	0.63	0.50
S6-C250×50×3-R6-N75	0.83	0.30	0.79	0.32	0.67	0.54

Table 4.38 Finite element load to ECP nominal web crippling ratios and corresponding moment ratios of series"S7"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$
S7-C100×50×2-R9-N25	0.90	0.37	0.57	0.56	0.40	0.79
S7-C100×50×2-R9-N50	0.96	0.42	0.64	0.64	0.45	0.90
S7-C100×50×2-R9-N75	1.00	0.47	0.71	0.72	0.46	0.93
S7-C150×50×2-R9-N25	0.89	0.27	0.78	0.41	0.57	0.61
S7-C150×50×2-R9-N50	0.97	0.31	0.87	0.47	0.61	0.66
S7-C150×50×2-R9-N75	1.03	0.34	0.90	0.49	0.66	0.72
S7-C200×50×2-R9-N25	0.91	0.22	0.87	0.29	0.72	0.48
S7-C200×50×2-R9-N50	0.99	0.25	0.95	0.32	0.78	0.53
S7-C200×50×2-R9-N75	1.04	0.27	0.99	0.34	0.81	0.56
S7-C250×50×2-R9-N25	0.93	0.18	0.91	0.20	0.81	0.36
S7-C250×50×2-R9-N50	1.01	0.20	1.00	0.23	0.95	0.43
S7-C250×50×2-R9-N75	1.07	0.23	1.03	0.24	0.89	0.41

Table 4.39 Finite element load to ECP nominal web crippling ratios and corresponding moment ratios of series"S8"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$
S8-C100×50×3-R9-N25	0.60	0.37	0.45	0.67	0.33	1.00
S8-C100×50×3-R9-N50	0.70	0.47	0.50	0.76	0.35	1.07
S8-C100×50×3-R9-N75	0.78	0.56	0.52	0.79	0.31	0.94
S8-C150×50×3-R9-N25	0.62	0.29	0.57	0.48	0.41	0.69
S8-C150×50×3-R9-N50	0.72	0.36	0.63	0.53	0.55	0.92
S8-C150×50×3-R9-N75	0.80	0.42	0.55	0.46	0.55	0.93
S8-C200×50×3-R9-N25	0.63	0.24	0.63	0.33	0.52	0.55
S8-C200×50×3-R9-N50	0.73	0.29	0.72	0.39	0.65	0.69
S8-C200×50×3-R9-N75	0.82	0.34	0.77	0.42	0.58	0.62
S8-C250×50×3-R9-N25	0.64	0.20	0.68	0.25	0.59	0.44
S8-C250×50×3-R9-N50	0.74	0.25	0.77	0.29	0.64	0.48
S8-C250×50×3-R9-N75	0.84	0.29	0.81	0.30	0.68	0.51

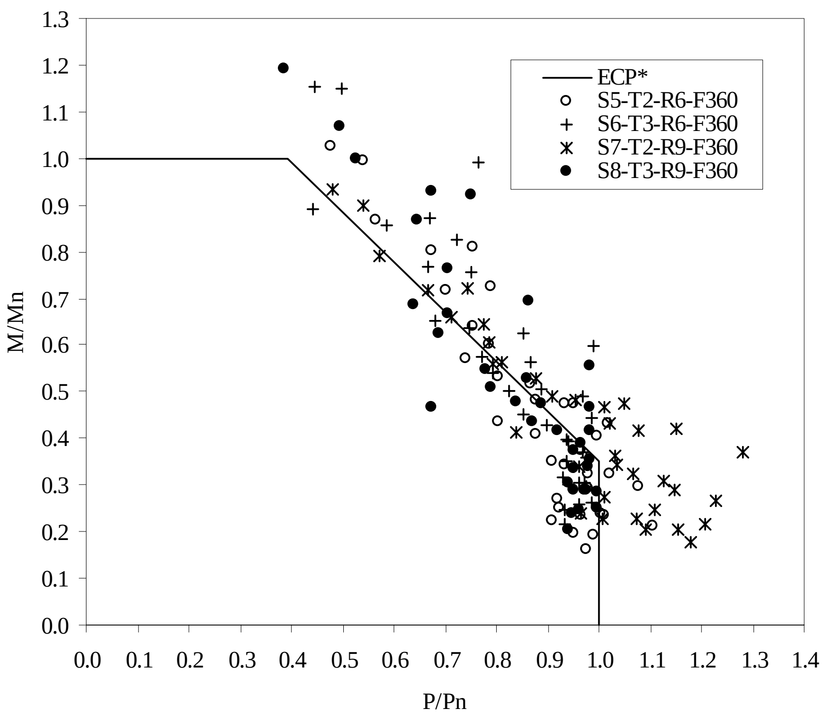

*Fig. 4.61 Finite element results versus interaction equation of ECP**

Tables 4.40 to 4.43 represented the ratios of the finite element load to the predicted web crippling strengths using NAS specification (P/P_n) and their corresponding moment ratios

(M/M_n). Figure 4.62 showed that NAS interaction equation for bending and web crippling was generally conservative.

Table 4.40 Finite element load to NAS nominal web crippling ratios and corresponding moment ratios of series"S5"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$
S5-C100×50×2-R6-N25	0.99	0.32	0.76	0.60	0.55	0.87
S5-C100×50×2-R6-N50	1.02	0.40	0.80	0.72	0.55	1.00
S5-C100×50×2-R6-N75	1.03	0.47	0.82	0.81	0.52	1.02
S5-C150×50×2-R6-N25	0.98	0.24	0.99	0.43	0.73	0.64
S5-C150×50×2-R6-N50	1.00	0.29	0.95	0.48	0.72	0.72
S5-C150×50×2-R6-N75	1.01	0.34	0.94	0.52	0.73	0.80
S5-C200×50×2-R6-N25	0.96	0.19	1.05	0.30	0.86	0.48
S5-C200×50×2-R6-N50	0.99	0.24	1.00	0.32	0.82	0.53
S5-C200×50×2-R6-N75	1.00	0.27	0.99	0.35	0.80	0.57
S5-C250×50×2-R6-N25	0.95	0.16	1.08	0.21	0.94	0.37
S5-C250×50×2-R6-N50	0.97	0.20	1.03	0.23	0.90	0.41
S5-C250×50×2-R6-N75	0.99	0.23	1.01	0.25	0.87	0.44

Table 4.38 Finite element load to NAS nominal web crippling ratios and corresponding moment ratios of series"S6"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$
S6-C100×50×3-R6-N25	0.90	0.39	0.72	0.76	0.43	0.89
S6-C100×50×3-R6-N50	0.95	0.49	0.65	0.77	0.49	1.15
S6-C100×50×3-R6-N75	1.00	0.60	0.77	0.99	0.45	1.15
S6-C150×50×3-R6-N25	0.90	0.30	0.85	0.51	0.70	0.82
S6-C150×50×3-R6-N50	0.95	0.37	0.85	0.56	0.65	0.87
S6-C150×50×3-R6-N75	1.00	0.44	0.86	0.62	0.59	0.86
S6-C200×50×3-R6-N25	0.90	0.25	0.90	0.35	0.74	0.58
S6-C200×50×3-R6-N50	0.94	0.30	0.91	0.40	0.73	0.64
S6-C200×50×3-R6-N75	0.99	0.36	0.91	0.43	0.69	0.65
S6-C250×50×3-R6-N25	0.90	0.21	0.95	0.26	0.82	0.45
S6-C250×50×3-R6-N50	0.94	0.26	0.95	0.30	0.80	0.50
S6-C250×50×3-R6-N75	0.99	0.30	0.94	0.32	0.80	0.54

Table 4.38 Finite element load to NAS nominal web crippling ratios and corresponding moment ratios of series"S7"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$
S7-C100×50×2-R9-N25	1.24	0.37	0.79	0.56	0.55	0.79
S7-C100×50×2-R9-N50	1.17	0.42	0.79	0.64	0.55	0.90
S7-C100×50×2-R9-N75	1.14	0.47	0.80	0.72	0.52	0.93
S7-C150×50×2-R9-N25	1.19	0.27	1.04	0.41	0.76	0.61
S7-C150×50×2-R9-N50	1.14	0.31	1.03	0.47	0.72	0.66
S7-C150×50×2-R9-N75	1.12	0.34	0.98	0.49	0.72	0.72
S7-C200×50×2-R9-N25	1.17	0.22	1.11	0.29	0.92	0.48
S7-C200×50×2-R9-N50	1.13	0.25	1.08	0.32	0.89	0.53
S7-C200×50×2-R9-N75	1.09	0.27	1.04	0.34	0.86	0.56
S7-C250×50×2-R9-N25	1.14	0.18	1.12	0.20	1.00	0.36
S7-C250×50×2-R9-N50	1.11	0.20	1.09	0.23	1.04	0.43
S7-C250×50×2-R9-N75	1.09	0.23	1.05	0.24	0.91	0.41

Table 4.38 Finite element load to NAS nominal web crippling ratios and corresponding moment ratios of series"S8"

Specimen label	Web Crippling		Span L = 1000 mm		Span L = 2000 mm	
	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$	$\frac{P}{P_n}$	$\frac{M}{M_n}$
S8-C100×50×3-R9-N25	0.92	0.37	0.68	0.67	0.51	1.00
S8-C100×50×3-R9-N50	0.97	0.47	0.69	0.76	0.49	1.07
S8-C100×50×3-R9-N75	1.00	0.56	0.66	0.79	0.39	0.94
S8-C150×50×3-R9-N25	0.92	0.29	0.86	0.48	0.62	0.69
S8-C150×50×3-R9-N50	0.97	0.36	0.85	0.53	0.74	0.92
S8-C150×50×3-R9-N75	1.00	0.42	0.69	0.46	0.69	0.93
S8-C200×50×3-R9-N25	0.92	0.24	0.92	0.33	0.75	0.55
S8-C200×50×3-R9-N50	0.96	0.29	0.95	0.39	0.85	0.69
S8-C200×50×3-R9-N75	1.00	0.34	0.94	0.42	0.70	0.62
S8-C250×50×3-R9-N25	0.91	0.20	0.97	0.25	0.84	0.44
S8-C250×50×3-R9-N50	0.95	0.25	0.98	0.29	0.83	0.48
S8-C250×50×3-R9-N75	1.00	0.29	0.96	0.30	0.81	0.51

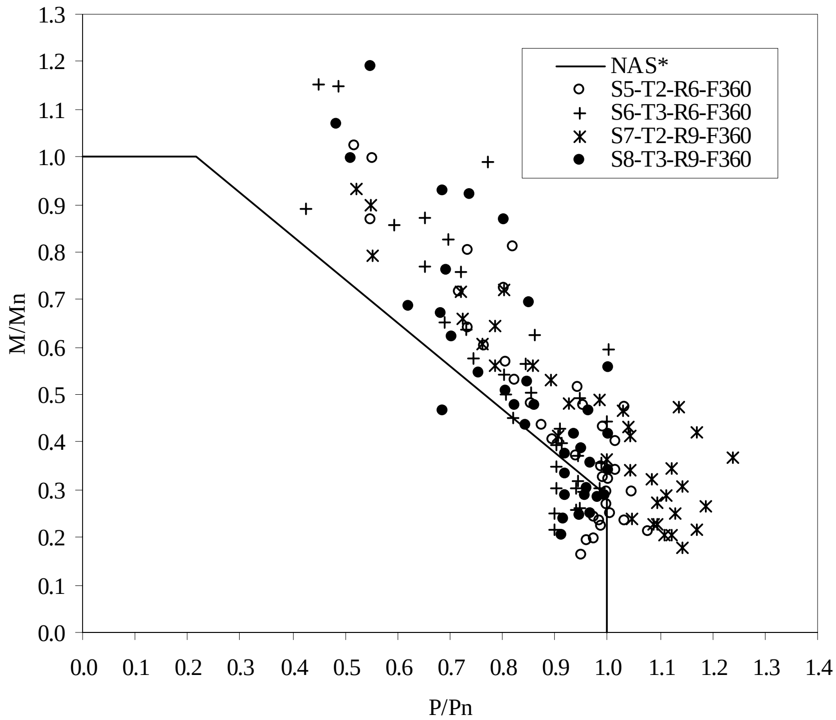

*Fig. 4.62 Finite element results versus interaction equation of NAS**

New proposed interaction equations (Eq.4.3 through 4.5) based on curve fitting were developed for both ECP** and NAS** specification. Figure 4.63 represented the comparison between finite element and the new proposed interaction equation. The following design equations should be satisfied in case of interaction of bending and web crippling according to LRFD method:

$$1.25\left(\frac{P_u}{\phi_w P_n}\right)+\left(\frac{M_u}{\phi_b M_n}\right)\leq 1.60 \tag{4.3}$$

$$\left(\frac{P_u}{\phi_W P_n}\right)\leq 1.0 \tag{4.4}$$

$$\left(\frac{M_u}{\phi_b M_n}\right)\leq 1.0 \tag{4.5}$$

Where:

Φ_b = Resistance factor for bending = 0.90

Φ_w = Resistance factor for web crippling =0.95

P_u = The ultimate concentrated load or reaction in the presence of bending moment.

P_n = Nominal web crippling strength for concentrated load or reaction in the absence of bending moment.

M_u = Required flexural strength at, or immediately adjacent to, the point of application of the concentrated load or reaction, P_u

M_n = Nominal flexural strength about the x-axis.

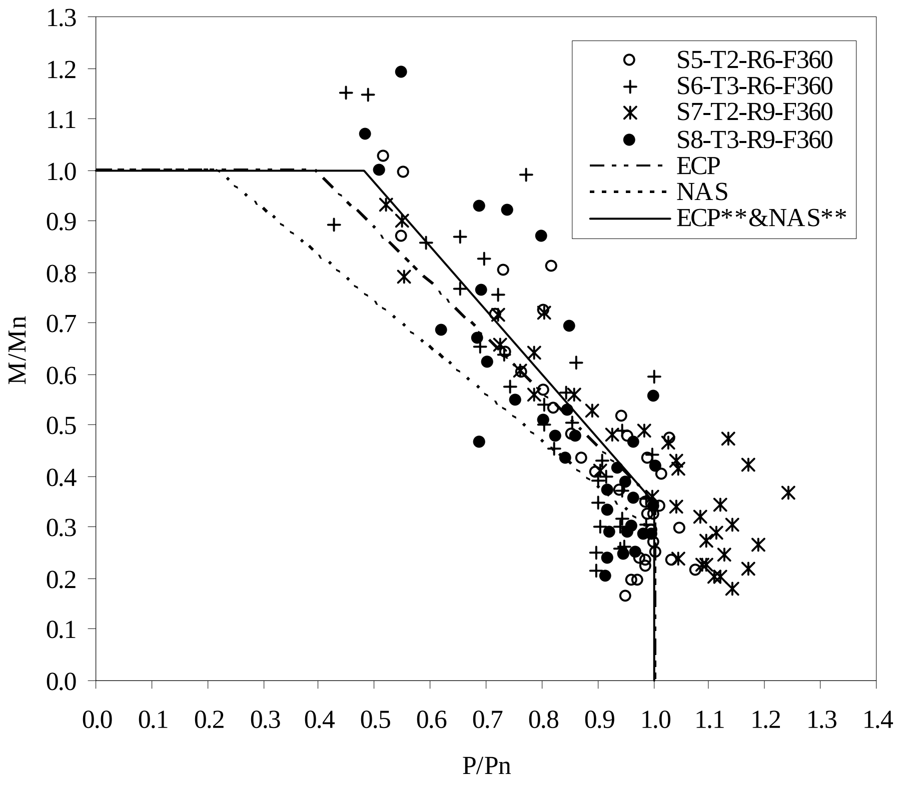

Fig. 4.63 Finite element results versus proposed interaction equations