CHAPTER FOUR
RESULTS, DISCUSSION, AND COMPARISON

4.1 Introduction

In this chapter the effect of attaching purlin to deck or sheeting is studied utilizing the finite element analysis. Comparison between members through fastened to deck or sheeting with and without tie rods is accomplished. The effect of tie rods on the buckling load is investigated. The results obtained were compared to the nominal strength according to AISI and Eurocode3. The nonlinear finite element analysis is then compared with the Eigen value finite element analysis to justify the applicability of the Eigen value analysis in estimating the strength of the structural members. The interactive buckling behavior under axial force and bending moment were also studied and compared to both AISI and Eurocode3.

4.2: Parametric Study

In order to determine what parameters had the most significant effects on the axial and flexural strength of purlins, a study was conducted to achieve this objective. Limitations specified by the American Iron and Steel Institute (AISI), Cold-Formed Steel Design Manual [7] and Cold-formed Thin-gauge Members and Sheeting [20] (Eurocode3, Part 1.3) were satisfied by chosen ranges of different parameters. Recommendations of J.A. Stolarczyk and J. M. Fisher [42] were also considered. So that the following range of parameters were chosen as being applicable:

1. Purlin flange width

   Range: 60 mm to 90 m

2. Purlin depth

   Range: 152 mm to 300 mm

3. Purlin thickness

Range: 1.5 mm to 3.0 mm

4. Diaphragm stiffness of roof

   Range: 0.20 t/cm/m to 0.80 t/cm/m

5. Rotational stiffness of the panel to purlin flange assembly

   Range: 1.80 t.cm/m/rad. to 3.30 t.cm/m/rad.

6. Purlin length

   Range: 6000 mm to 10000 mm

7. Spacing of bolt

   Range: 200 mm to 300 mm

Within this range of parameters, certain values were chosen. Finite element models were developed for all combinations of these parameters except for purlin thickness of 1.5 mm which was used only with purlin flange width of 6 cm and purlin depth of 20 cm. This means that the limits of purlin flange width / thickness and purlin depth / thickness were not violated.

4.2.1 Eigen analysis

Table 4.1 showed parameters used for modeling free members. This combination of parameters gave 26 models. All these models were analyzed under axial loading and flexural loading. Total number of free models was 52 models. Refer to Appendix A (test 1: 52).

Table 4.1 Parameters and associated values for finite element Eigen analysis of free members

Parameter	Values
Purlin flange width	60 – 90 mm
Purlin depth	200 – 300 mm
Purlin thickness	1.5 – 2.0 – 2.5 – 3.0 mm
Purlin length	6000 – 9000 mm

Table 4.2 showed the parameters used for modeling members attached to deck or sheeting. Combinations of these parameters gave 208 varieties. For each combination a model was developed for each type of loading (axial load and flexural uplift), i.e., 416 models were developed. Each of 416 models was analyzed two times, one without using tie rods and the other with using tie rods. Tie rods were located each 3 m along the purlin length. Only one tie rod was used for 6 m span purlins located at the middle of the purlin. Two tie rods were used for 9 m along the purlin length located at one-third and two-third of purlin span. Total number of Eigen models is 832 models. Appendix A listed the test matrix of these models (test 53: 884).

Table 4.2 Parameters and associated values for finite element Eigen analysis of attached members

Parameter	Values
Purlin flange width	60 – 90 mm
Purlin depth	200 – 300 mm
Purlin thickness	1.5 – 2.0 – 2.5 – 3.0 mm
Diaphragm stiffness of roof	0.00020 to 0.00080 t/mm/mm
Rotational stiffness of the panel to purlin flange assembly	0.18 to 0.33 t.mm/mm/rad.
Purlin length	6000 – 9000 mm
Spacing of bolt	200 – 300 mm

4.2.2 Nonlinear analysis

Nonlinear finite element analysis was performed for some models. Nonlinear analysis takes usually longer time than Eigen analysis. So that the number of tested models using nonlinear analysis were smaller than those of Eigen analysis. Parameters used for Eigen analysis were used in nonlinear analysis, but with smaller ranges. Table 4.3 shows parameters used for nonlinear analysis. Combination of these parameters gave s 13 varieties. Each of this combination was tested under axial loaded and flexural loaded, without using tie rods. These combinations were also analyzed under axial load and flexural load by using tie rods at the middle of the span. A total of 52 models were analyzed using nonlinear finite element analysis. Appendix A listed the test matrix of these models (from test 885:936).Although the Z-section is a point symmetric section, attaching sheeting to one flange made unsymmetrical model. So that it was not necessary to apply initial imperfection.

Table 4.3 Parameters and associated values for finite element nonlinear analysis

Parameter	Values
Purlin flange width	60 – 90 mm
Purlin depth	200 – 300 mm
Purlin thickness	1.5 – 2.0 – 2.5 – 3.0 mm
Diaphragm stiffness of roof	0.20 t/cm/m
Rotational stiffness of the panel to purlin flange assembly	1.80 t.cm/m/rad.
Purlin length	6000 mm
Spacing of bolt	200 mm

4.3 Effect of Deck or Sheeting

Under either axial load or flexural load, free purlins were analyzed. The axial and flexural strength of free purlins were compared to the strength of purlins through fastened to deck or sheeting with different roof lateral and rotational stiffness, and fastener spacing.

Table 4.4 shows the results of axially loaded members. It could be observed from this table that the axial buckling load ratio of members attached to deck or sheeting to free members increased by a ratio of 1.048 to 6.809. The average increase of axial buckling load was in the range of 1.072 to 4.704. As the roof lateral stiffness increased the member axial buckling load increased, and as the roof rotational stiffness increased the member axial buckling load increased. The roof lateral stiffness had minor effect on member axial buckling load, but roof rotational stiffness had great influence on member's axial buckling load. As the pitch of fastener increased the member axial buckling load decreased.

Table 4.4 the axial buckling load ratio of members attached to sheeting to free members, from finite element Eigen value analysis

Kd (t/cm/m)	**0.2**	**0.2**	**0.2**	**0.2**	**0.8**	**0.8**	**0.8**	**0.8**			
Kr (t.cm/m/rad)	**1.8**	**1.8**	**3.3**	**3.3**	**1.8**	**1.8**	**3.3**	**3.3**			
p (cm)	**20**	**30**	**20**	**30**	**20**	**30**	**20**	**30**			
Test No.									**Min**	**Max**	**Avrg**
1_Z-200x60x1.5	2.651	2.628	2.651	2.627	2.651	2.630	2.651	2.629	**2.627**	**2.651**	**2.640**
2_Z-200x60x2	4.682	3.251	4.721	3.366	4.682	3.358	4.682	4.623	**3.251**	**4.721**	**4.171**
3_Z-200x60x2.5	5.657	2.894	6.269	2.974	6.102	2.988	6.809	3.072	**2.894**	**6.809**	**4.596**
4_Z-200x60x3	5.418	2.639	5.917	2.694	5.913	2.721	6.512	2.779	**2.639**	**6.512**	**4.324**
5_Z-200x90x2	2.374	2.014	2.374	2.030	2.374	2.066	2.374	1.582	**1.582**	**2.374**	**2.149**
6_Z-200x90x2.5	3.688	1.840	3.694	1.853	3.693	1.883	3.694	1.398	**1.398**	**3.694**	**2.718**
7_Z-200x90x3	3.491	1.717	3.596	1.726	3.931	1.754	4.073	1.265	**1.265**	**4.073**	**2.694**
8_Z-300x60x2	2.318	2.282	2.318	2.281	2.318	2.281	2.318	2.282	**2.281**	**2.318**	**2.300**
9_Z-300x60x2.5	3.543	2.618	3.544	2.670	3.543	2.696	3.544	2.750	**2.618**	**3.544**	**3.113**
10_Z-300x60x3	4.709	2.405	4.957	2.440	4.960	2.474	4.962	2.512	**2.405**	**4.962**	**3.677**
11_Z-300x90x2	1.094	1.050	1.094	1.048	1.094	1.051	1.094	1.050	**1.048**	**1.094**	**1.072**
12_Z-300x90x2.5	1.692	1.606	1.691	1.603	1.692	1.608	1.692	1.605	**1.603**	**1.692**	**1.649**
13_Z-300x90x3	2.411	1.642	2.411	1.648	2.411	1.674	2.411	1.681	**1.642**	**2.411**	**2.036**
14_Z-200x60x1.5	4.614	4.601	4.769	4.754	4.653	4.640	4.810	4.795	**4.601**	**4.810**	**4.704**
15_Z-200x60x2	3.808	3.804	3.920	3.916	3.839	3.836	3.952	3.948	**3.804**	**3.952**	**3.878**
16_Z-200x60x2.5	3.292	3.291	3.374	3.371	3.319	3.317	3.400	3.398	**3.291**	**3.400**	**3.345**
17_Z-200x60x3	2.937	2.936	2.996	2.994	2.959	2.958	3.018	3.017	**2.936**	**3.018**	**2.977**
18_Z-200x90x2	2.161	2.160	2.188	2.187	2.174	2.174	2.201	2.200	**2.160**	**2.201**	**2.180**
19_Z-200x90x2.5	1.948	1.948	1.967	1.967	1.959	1.959	1.979	1.978	**1.948**	**1.979**	**1.963**
20_Z-200x90x3	1.801	1.801	1.800	1.815	1.810	1.810	1.824	1.824	**1.800**	**1.824**	**1.811**
21_Z-300x60x2	3.356	3.352	3.476	3.470	3.385	3.382	3.505	3.499	**3.352**	**3.505**	**3.428**
22_Z-300x60x2.5	2.939	2.938	3.024	3.022	2.962	2.961	3.094	3.044	**2.938**	**3.094**	**2.998**
23_Z-300x60x3	2.651	2.651	2.713	2.711	2.672	2.671	2.732	2.732	**2.651**	**2.732**	**2.692**
24_Z-300x90x2	2.037	2.036	2.062	2.061	2.050	2.049	2.074	2.074	**2.036**	**2.074**	**2.055**
25_Z-300x90x2.5	1.846	1.846	1.864	1.864	1.856	1.856	1.874	1.874	**1.846**	**1.874**	**1.860**
26_Z-300x90x3	1.716	1.716	1.729	1.729	1.725	1.725	1.737	1.737	**1.716**	**1.737**	**1.727**

Table 4.5 shows the results of flexurally loaded members. It could be observed from this table that the flexural buckling load ratio of members attached to deck or sheeting to free members increased by a ratio of 1.12 to 4.172. The average increase of the flexural buckling load was in the range of 1.207 to 3.823. As the roof lateral stiffness increased the member flexural buckling load increased, and as the roof rotational stiffness increased the member's flexural buckling load increased. The roof lateral stiffness had minor effect on member flexural buckling load, but roof rotational

stiffness had greater influence on member flexural buckling load. As the pitch of fastener increased the member flexural buckling load decreased.

Table 4.5 the flexural buckling load ratio of members attached to sheeting to free members, from finite element Eigen value analysis

Kd (t/cm/m)	0.2	0.2	0.2	0.2	0.8	0.8	0.8	0.8			
Kr (t.cm/m/rad)	1.8	1.8	3.3	3.3	1.8	1.8	3.3	3.3			
p (cm)	20	30	20	30	20	30	20	30			
Test No.									Min	Max	Avrg
27_Z-200x60x1.5	1.979	1.765	2.199	1.908	2.028	1.784	2.259	1.927	**1.765**	**2.259**	**1.981**
28_Z-200x60x2	1.915	1.663	2.159	1.821	1.973	1.680	2.232	1.839	**1.663**	**2.232**	**1.910**
29_Z-200x60x2.5	1.835	1.565	2.062	1.711	1.898	1.580	2.141	1.728	**1.565**	**2.141**	**1.815**
30_Z-200x60x3	1.775	1.492	1.975	1.620	1.842	1.506	2.058	1.635	**1.492**	**2.058**	**1.738**
31_Z-200x90x2	1.157	1.251	1.192	1.310	1.120	1.259	1.151	1.318	**1.120**	**1.318**	**1.220**
32_Z-200x90x2.5	1.364	1.204	1.447	1.261	1.411	1.210	1.451	1.268	**1.204**	**1.451**	**1.327**
33_Z-200x90x3	1.333	1.165	1.407	1.218	1.383	1.170	1.462	1.223	**1.165**	**1.462**	**1.295**
34_Z-300x60x2	1.658	1.482	1.761	1.548	1.699	1.495	1.806	1.563	**1.482**	**1.806**	**1.627**
35_Z-300x60x2.5	1.641	1.423	1.743	1.489	1.690	1.436	1.797	1.502	**1.423**	**1.797**	**1.590**
36_Z-300x60x3	1.617	1.369	1.709	1.429	1.670	1.381	1.769	1.442	**1.369**	**1.769**	**1.548**
37_Z-300x90x2	1.386	1.321	1.434	1.276	1.352	1.329	1.397	1.284	**1.276**	**1.434**	**1.347**
38_Z-300x90x2.5	1.242	1.158	1.274	1.183	1.205	1.165	1.235	1.190	**1.158**	**1.274**	**1.207**
39_Z-300x90x3	1.354	1.123	1.387	1.146	1.409	1.128	1.444	1.157	**1.123**	**1.444**	**1.269**
40_Z-200x60x1.5	3.530	3.494	4.149	4.077	3.548	3.511	4.172	4.101	**3.494**	**4.172**	**3.823**
41_Z-200x60x2	3.159	3.144	3.813	3.778	3.174	3.159	3.834	3.798	**3.144**	**3.834**	**3.482**
42_Z-200x60x2.5	2.820	2.814	3.413	3.396	2.833	2.826	3.430	3.413	**2.814**	**3.430**	**3.118**
43_Z-200x60x3	2.549	2.546	3.059	3.050	2.559	2.557	3.074	3.065	**2.546**	**3.074**	**2.807**
44_Z-200x90x2	1.524	1.519	1.741	1.730	1.528	1.524	1.746	1.735	**1.519**	**1.746**	**1.631**
45_Z-200x90x2.5	1.437	1.436	1.643	1.639	2.062	1.440	1.648	1.642	**1.436**	**2.062**	**1.618**
46_Z-200x90x3	1.370	1.369	1.557	1.554	1.373	1.373	1.560	1.557	**1.369**	**1.560**	**1.464**
47_Z-300x60x2	2.526	2.519	2.882	2.863	2.538	2.530	2.894	2.875	**2.519**	**2.894**	**2.703**
48_Z-300x60x2.5	2.356	2.353	2.696	2.686	2.366	2.364	2.705	2.696	**2.353**	**2.705**	**2.528**
49_Z-300x60x3	1.613	1.612	1.835	1.830	1.619	1.619	1.840	1.837	**1.612**	**1.840**	**1.726**
50_Z-300x90x2	1.350	1.349	1.457	1.452	1.354	1.353	1.461	1.456	**1.349**	**1.461**	**1.404**
51_Z-300x90x2.5	1.302	1.302	1.410	1.407	1.306	1.306	1.413	1.411	**1.302**	**1.413**	**1.357**
52_Z-300x90x3	1.262	1.263	1.363	1.362	1.265	1.265	1.366	1.364	**1.262**	**1.366**	**1.314**

4.4 Effect of Tie Rods

Effect of tie rods on the strength of members is investigated in this section. The axial strength was covered by 416 tests. Half of axial tests were performed for members without tie rods (tests 1 to 208). The second half of axial tests was performed for members with tie rods (tests 209 to 416). The last 416 tests covered the flexural strength of uplift loaded members. Half of flexural strength tests were performed for members without tie rods (tests 417 to 624). The second half of flexural strength tests was performed for members with tie rods (from test 625 to 832). For purlins with 6.0 m span only one tie rod at the middle is used. For purlins 9.0 m span two tie rods were used at the thirds of the span.

Comparison between the axial strength of members without tie rods and axial strength of members with tie rods was accomplished. Figure 4.1 shows the axial strength of members without tie rods on X-axis, and the axial strength of members with tie rods on Y-axis. The presence of tie rods has increased the axial strength by different values. Based on the rate of increase achieved by tie rods in member strength the tested members may be classified into five groups:

- The 1st group includes 56 tests (i.e. 27% of axial tests). In this group, members without tie rods have local web buckling mode and members with tie rods have also local web buckling mode. So that tie rods have no effect on the axial strength of members, because it is governed by local buckling mode.

- The 2nd group includes 67 tests (i.e. 32% of axial tests). In this group, members without tie rods have torsional-flexural buckling mode. While members with tie rods have local web buckling mode. So that tie rods have increased the axial strength of these members by values from 0.0 to 100%.

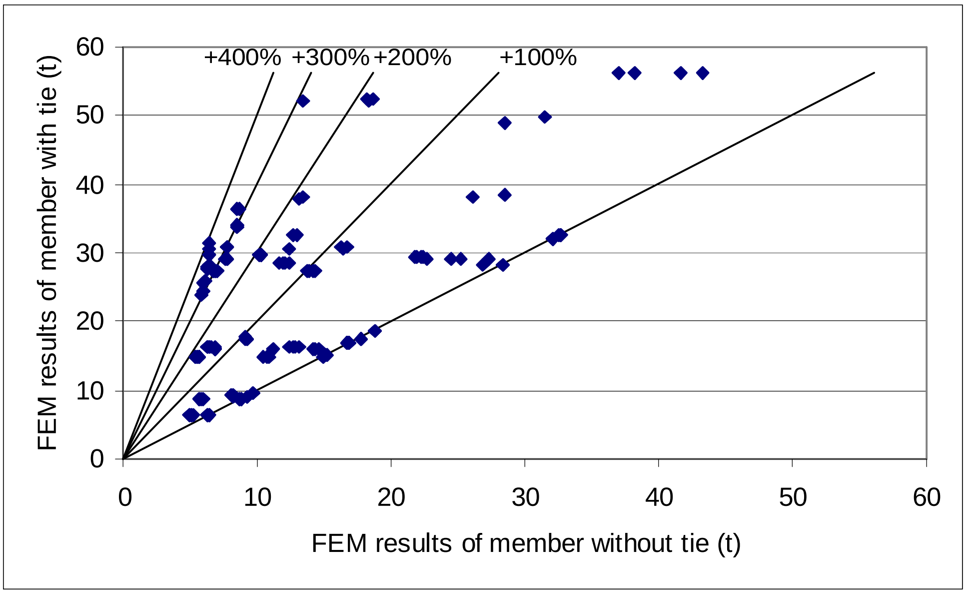

Fig. 4.1 FEM results of members without tie rods versus FEM results of members with tie rods of axially loaded member

- The 3rd group includes 44 tests (i.e. 21% of axial tests). In this group, members without tie rods have torsional-flexural buckling mode. While 39 members with tie rods have local web buckling mode and only five members with tie rods have torsional-flexural buckling mode with two half waves. So that tie rods have increased the axial strength of these members by a value from 100 to 200%.

- The 4th group includes 17 tests (i.e. 8% of axial tests). In this group, members without tie rods have torsional-flexural buckling mode. While nine members with tie rods have local web buckling mode and eight members with tie rods have torsional-flexural buckling mode with three half waves. So that tie rods have increased the axial strength of these members by value from 200 to 300%.

- The 5th group includes 24 tests (i.e. 12% of the axial tests). In this group, members without tie rods have torsional-flexural buckling mode. While 20 members with tie rods have torsional-flexural buckling mode with three half waves and only four members with tie rods have local web buckling mode. So that tie rods have increased the axial strength of these members by value from 300 to 385%.

These results showed that tie rods had no effect on members undergoing local web buckling (web depth/thickness ratio more than 120). The axial strength of these members with tie rods was nearly the same as those members without tie rods.

Members having lower web depth/thickness ratio were subjected to overall buckling (torsional-flexural buckling). Critical buckling load of overall buckling mode is strongly affected by laterally unrestrained length of the member. Tie rods had increased axial strength of these members by reducing laterally unrestrained length. Amount of increase in strength depended on web depth/thickness ratio and the reduction in the laterally unrestrained length. When web depth/thickness ratio was just enough to eliminate local web buckling, tie rods had limited effect on these members. Overall buckling of such members without tie rods were converted to local web buckling of members with tie rods with slight increase in member axial strength. While tie rods had greater effect on members with low web depth/thickness ratio such that local buckling was avoided for both members with and without tie rods (web depth/thickness ratio less than 100). Overall buckling was the governing buckling mode for these members. Reduction of laterally unrestrained length by using tie rods, results in large increase in members' axial strength.

Comparison between the flexural resistance of members without tie rods and flexural resistance of members with tie rods was performed. Figure 4.2 shows the flexural results of members without tie rods on X-axis, and the flexural results of members with tie rods on Y-axis. The presence of tie rods has increased the flexural strength by different values. Based on the rate of increase in member flexural strength the tested members may be distinguished into five groups as shown in Figure 4.2.

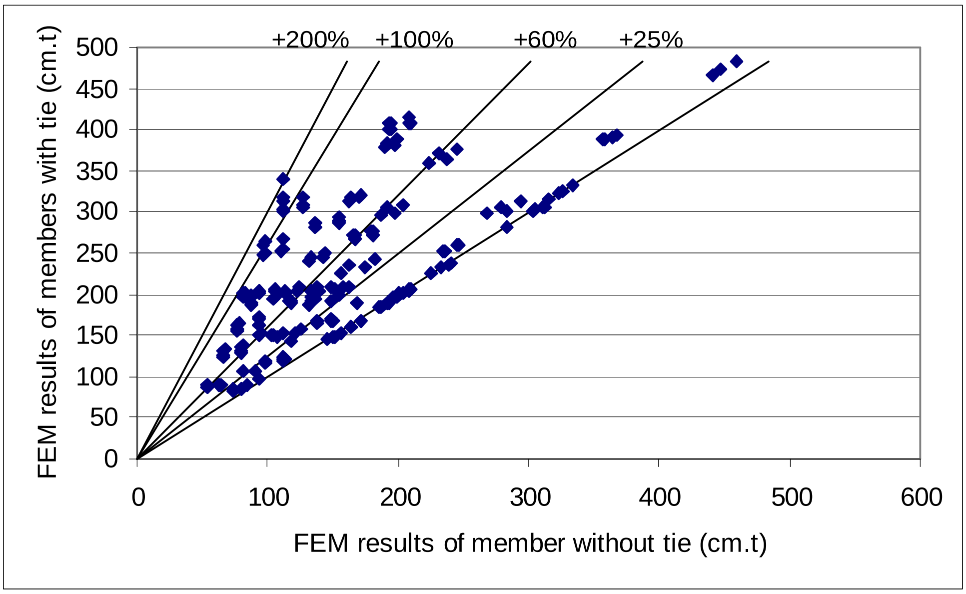

Fig. 4.2 FEM results of members without tie rods versus FEM results of members with tie rods of flexural uplift loaded members

- The 1st group includes 33 tests (i.e. 16% of flexural tests). In this group, members without tie rods undergo distortional buckling mode and members with tie rods undergo also distortional buckling mode. So that tie rods have no effect on the flexural strength of members.

- The 2nd group includes 39 tests (i.e. 18.8% of flexural tests). In this group, members without tie rods undergo lateral-torsional buckling mode. While members with tie rods undergo distortional buckling mode. So that tie rods have increased the flexural strength of these members by a value up to 25%.

- The 3rd group includes 50 tests (i.e. 24% of flexural tests). In this group, members without tie rods undergo lateral-torsional buckling mode. While 28 members with tie rods undergo distortional buckling mode and 22 members with tie rods undergo lateral-torsional buckling mode with two half waves. Tie rods have increased the flexural strength of these members by value from 25 to 60%.

- The 4th group includes 47 tests (i.e. 22.6% of flexural tests. In this group, members without tie rods undergo lateral-torsional buckling mode. While 16 members with tie rods undergo distortional buckling mode, and 31 members with tie rods undergo lateral-torsional buckling mode with two or three half waves. So that tie rods have increased the flexural strength of these members by a value from 60 to 100%.

- The 5th group includes 39 tests (i.e. 18.8% of flexural tests). In this group, members without tie rods undergo lateral-torsional buckling mode. While 13 members with tie rods undergo distortional buckling mode, and 26 members with tie rods undergo lateral-torsional buckling mode with three half waves. So that tie rods have increased the flexural strength of these members by value from 100 to 200%.

These results showed that tie rods had no effect on members subjected to distortional buckling (flange width/thickness ratio more than 36). The flexural strength of these members with tie rods was nearly the same as those members without tie rods. Members having higher flange width/thickness ratio were subjected to distortional buckling in the presence and absence of tie rods. These member flexural strengths were not affected by tie rods.

Members having lower flange width/thickness ratio were subjected to overall flexural buckling (lateral-torsional buckling). Critical buckling load of overall flexural buckling mode is strongly affected by laterally unsupported length of the member. Tie rods had increased flexural strength of these members by reducing laterally unsupported length. The amount of increase in flexural strength depends on flange width/thickness ratio and reduction in the laterally unsupported length. When flange width/thickness ratio was just enough to eliminate flange distortional buckling, tie rods had limited effect on these. Overall flexural buckling of members without tie rods was converted to distortional buckling of members with tie rods with slight increase in member flexural strength. While tie rods had greater effect on members with low flange width/thickness ratio such that local buckling was avoided for both members with and without tie rods (flange width/thickness ratio less than 30). Overall flexural buckling was the governing buckling mode for these members. Reduction of laterally unsupported length by using tie rods, results in large increase in member flexural strength.

4.5 Finite Element versus AISI (2007)

A comparison between the strength of members obtained from finite element analysis of members and the nominal strength of members according to AISI standard (North American specification for the design of cold-formed steel structural members) has been performed.

It should be mentioned here that, the utilized finite element analysis in this section is an Eigen value type analysis; therefore the obtained critical buckling load could be higher than the yield load. In some tests the finite element buckling load was greater than 70% of the material yield strength. In these cases, the finite element buckling load will provide a misleading failure load, because these members will actually fail due to material yielding. Buckling will nearly have no effect on the failure of these members. On the other hand, when the ultimate resistance is governed by the elastic stability, the obtained critical buckling load will reasonably represent the failure load. Accordingly, the tests of critical loads higher than the yield strength will be omitted from the following comparison.

4.5.1 Axially Loaded Members

The strength of members obtained from finite element analysis of each member of this group have been compared with the axial strength of the member calculated from the AISI standard. The axial strength according to AISI standard was the least of two values. The first was the X-axis strength of the member which presents the flexural buckling load about the strong axis. This value was considered because the flexural bucking about the weak axis as an individual mode was prevented by the continuous lateral stiffness of the sheeting. The second value was the lateral-torsional capacity of the member. This value presents the interactive buckling strength of the flexural bucking about the weak axis and torsional buckling about the longitudinal axis. The effect of lateral and torsional stiffness provided by the sheeting was considered on this interactive buckling mode.

Comparison between strength of members obtained from finite element analysis and AISI strength of 416 axially loaded members was shown in figure 4.3. In this figure finite element results were assigned to X-direction and AISI standard results were assigned to Y-direction. It could be observed from the figure that AISI gave very conservative results for 64% of tested members. About 14% of members of this group gave conservative values with decrease of less than 20%, and about 12% gave non-conservative values with increase of less than 20%. It is evident that only 26% of the results lie inside the 20% confidence envelopes, while 10% of tested members lie in the very non-conservative zone.

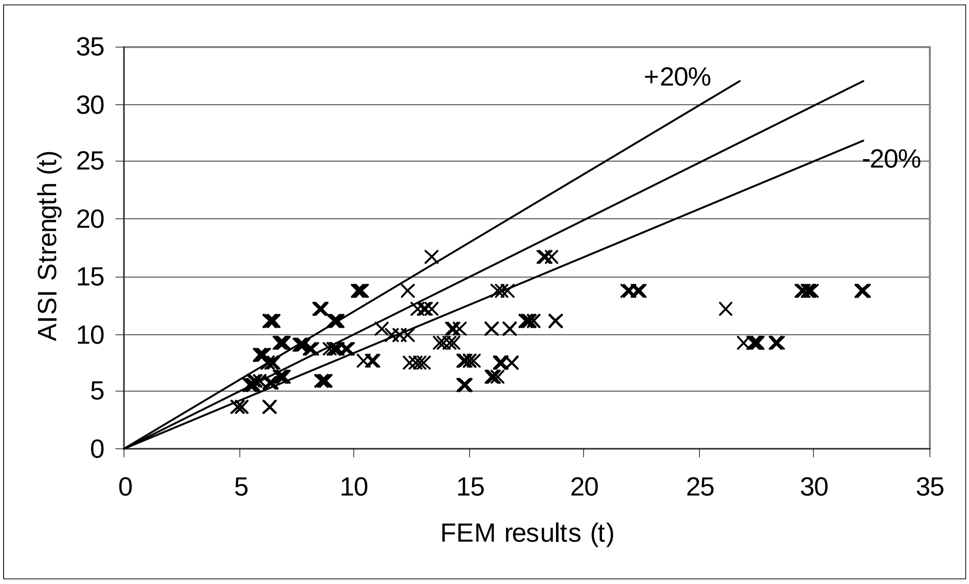

Fig. 4.3 FEM results versus AISI strength of axially loaded members

Members of this group have been divided into four subgroups based on the presence or absence of tie rods and the web depth to thickness ratio (d/t). AISI did not consider the effect of tie rods on the axial strength of members attached to deck or sheathing. In this section finite element results of members restrained by tie rods were compared with AISI axial strength, in order to reveal the benefits which were lost by neglecting the effect of tie rods. In each of the following figures finite element results were assigned to X-direction and AISI standard results were assigned to Y-direction. Table 4.6 shows some statistic factors for the ratio of FEM results to AISI strength of axially loaded members of these subgroups.

Table 4.6 the ratio of FEM results to AISI strength of axially loaded members

P/Pn		Maximum	Minimum	Average	S.D	Correlation
Without Tie rods	d/t < 100	3.070	0.568	1.309	0.676	0.574
	d/t > 100	2.239	0.817	1.225	0.372	0.638
With Tie rods	d/t < 100	4.104	1.538	2.673	0.516	0.814
	d/t > 100	2.242	1.027	1.548	0.396	0.752

Results of 128 members without tie rods having web depth to thickness ratio of less than or equal to 100 were presented in figure 4.4. As shown in the Figure about 31% of the members lie in the non-conservative zone. 14% of these members lie in the permissible zone with a difference between the AISI standard strength and the strength of members obtained from finite element analysis of less than +20%. While

15% of these members showed difference of less than –20%. The rest of the members (about 40%) located in the conservative zone.

Histogram for the ratio of FEM results to AISI strength of axially loaded members with depth to thickness ratio of less than or equal to 100 was shown in figure 4.5. It could be observed from this Figure that the ratio of Finite element analysis results under axial load to AISI axial strength ratio was between 0.268 and 3.07 with an average value of (1.31). This subgroup had large standard deviation of (0.676) and low correlation, (correlation factor = 0.574).

Results of 80 members without tie rods having web depth to thickness ratio more than 100 were presented in Figure 4.6. As shown in the figure 37% of these members lie in the permissible zone with a difference between the AISI standard strength and the strength of members obtained from finite element analysis of less than +20%. While 23% of these members showed difference of less than –20%. The rest of the members (about 40%) located in the conservative zone.

Histogram for the ratio of FEM results to AISI strength of axially loaded members with web depth to thickness ratio of more than 100 was shown in Figure 4.7. It could be observed from this figure that the ratio of Finite element analysis results under axial load to AISI axial strength ratio was in the range of (0.817 – 2.24) with an average value of (1.23). This subgroup had low standard deviation of (0.372) and low correlation (correlation factor = 0.638).

Figure 4.8 showed the relation ship between the web depth to thickness ratio and the axial strength of members according to AISI and finite element Eigen analysis results. As shown in figure the axial resistance of members decreased as the web depth to thickness ratio increased. The accuracy of results also increased as the web depth to thickness ratio increased

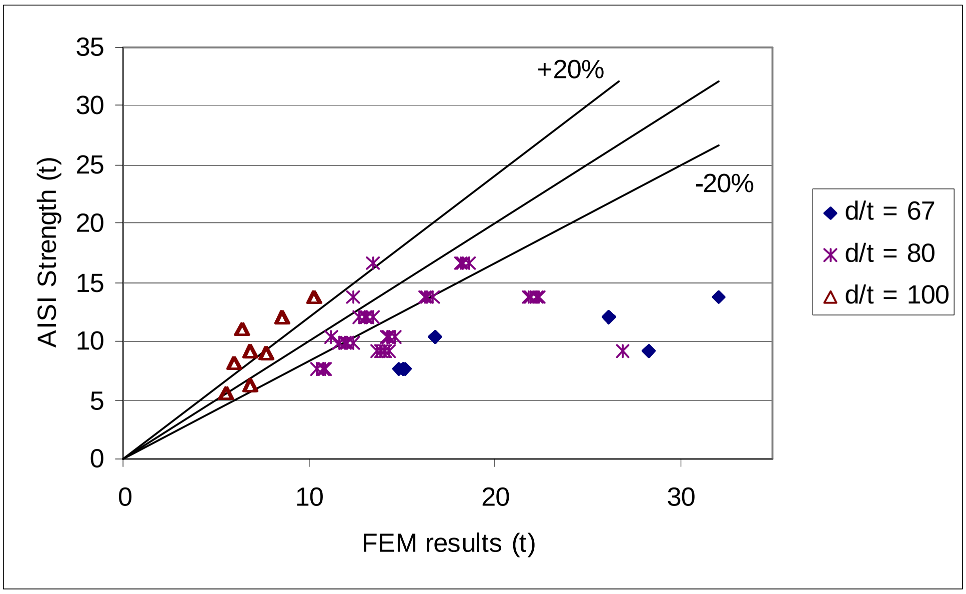

Fig. 4.4 FEM results versus AISI strength of axially loaded members (d/t < 100)

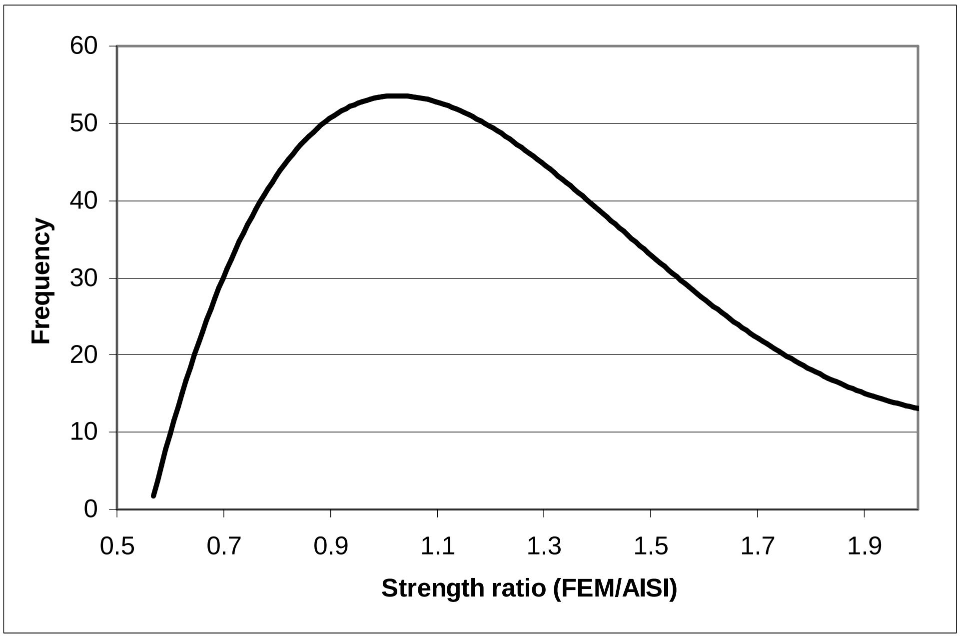

Fig. 4.5 Histogram for the ratio of FEM results to AISI strength of axially loaded member (d/t < 100)

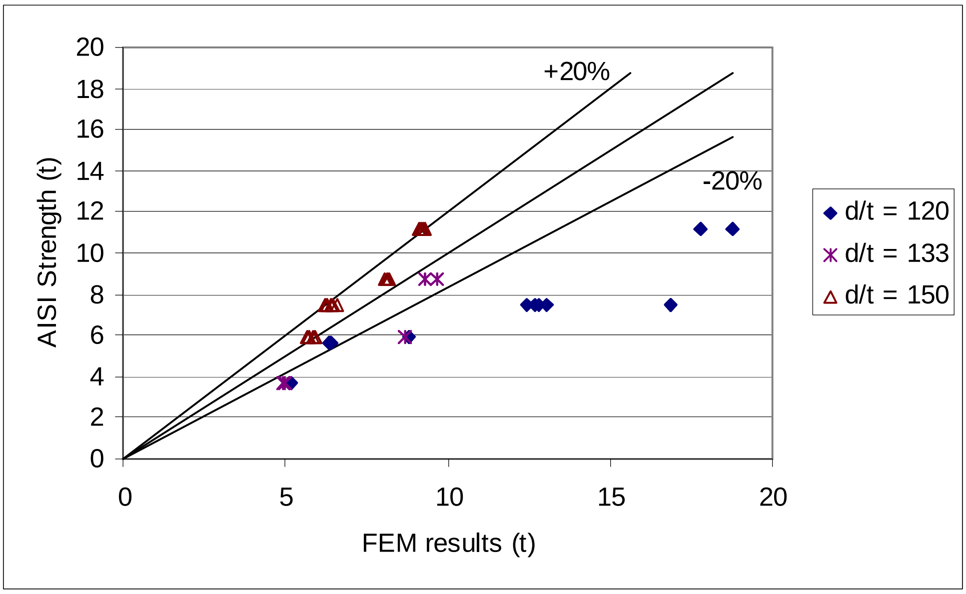

Fig. 4.6 FEM results versus AISI strength of axially loaded members (d/t > 100)

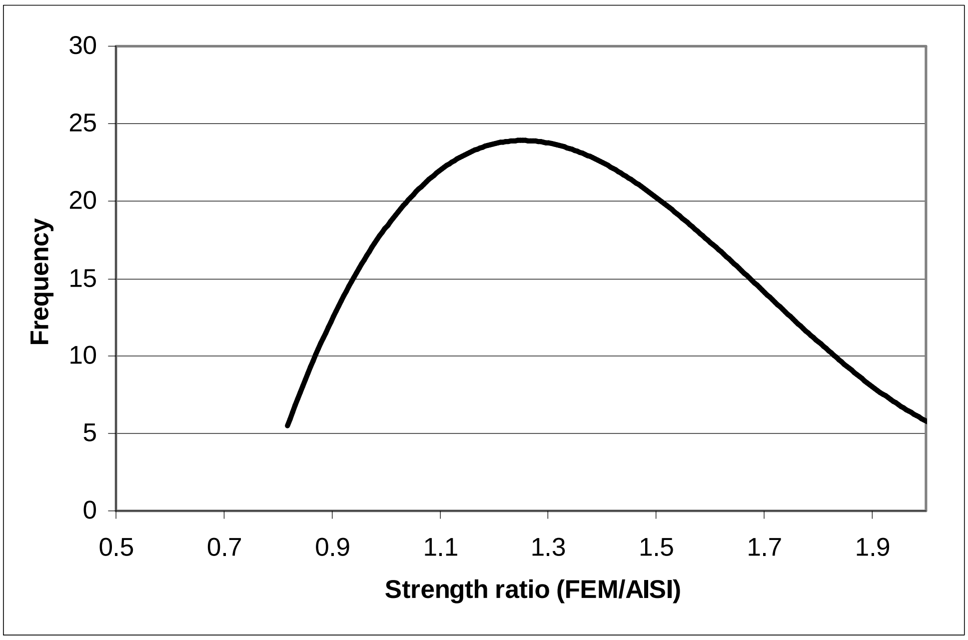

Fig. 4.7 Histogram for the ratio of FEM results to AISI strength of axially loaded members (d/t > 100)

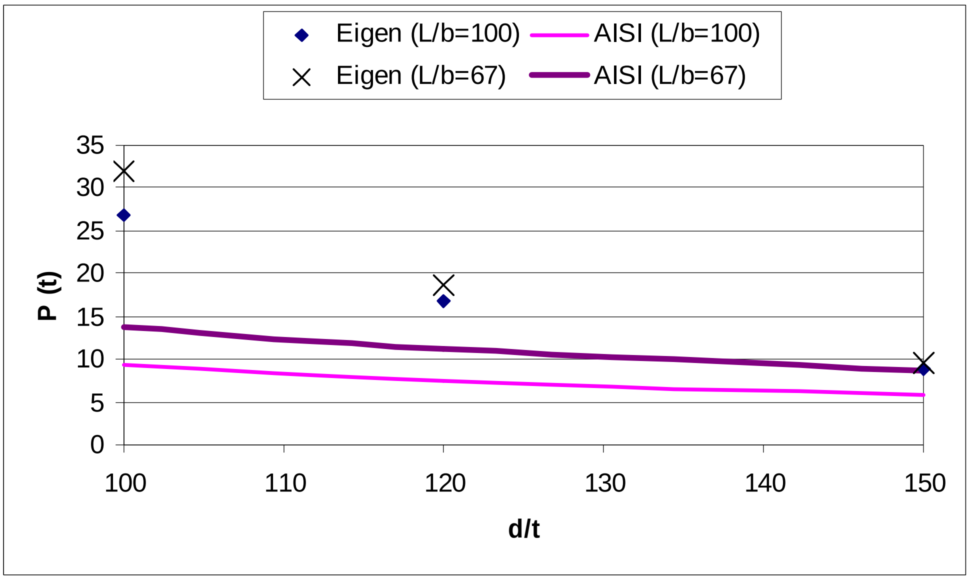

Fig. 4.8 FEM results and AISI strength of axially loaded members versus web depth to thickness ratio

Results of 128 members with tie rods having web depth to thickness ratio of less than or equal to 100 were presented in figure 4.9. As shown in the figure all of the members of these subgroups lie in the conservative zone.

Histogram for the ratio of FEM results to AISI strength of axially loaded members with depth to thickness ratio of less than or equal to 100 was shown in figure 4.10. It could be observed from this figure that the ratio of Finite element analysis results under axial load to AISI axial strength ratio was in the range of (1.54 – 4.10) with an average value of (2.67). This subgroup had large standard deviation of (0.516) and good correlation factor of 0.814.

Results of 80 members with tie rods having web depth to thickness ratio more than 100 were presented in figure 4.11. It could be observed from this Figure that 70% of tested members gave very conservative values. About 30% of members of this group gave conservative values with decrease of less than 20%, and none gave non-conservative values.

Histogram for the ratio of FEM results to AISI strength of axially loaded members with depth to thickness ratio of more than 100 was shown in figure 4.12. It could be observed from this Figure that the ratio of Finite element analysis results under axial load to AISI axial strength ratio was in the range of (1.03 – 2.24) with an average value of (1.55). This subgroup had low standard deviation of (0.396) and average correlation (correlation factor = 0.752).

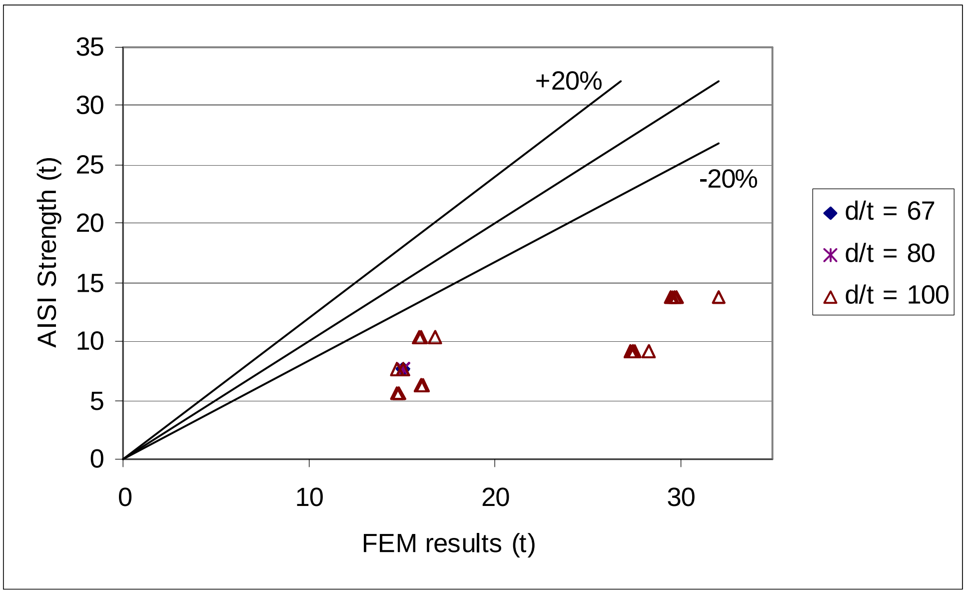

Fig. 4.9 FEM results versus AISI strength of axially loaded members (d/t < 100 for members with tie rods)

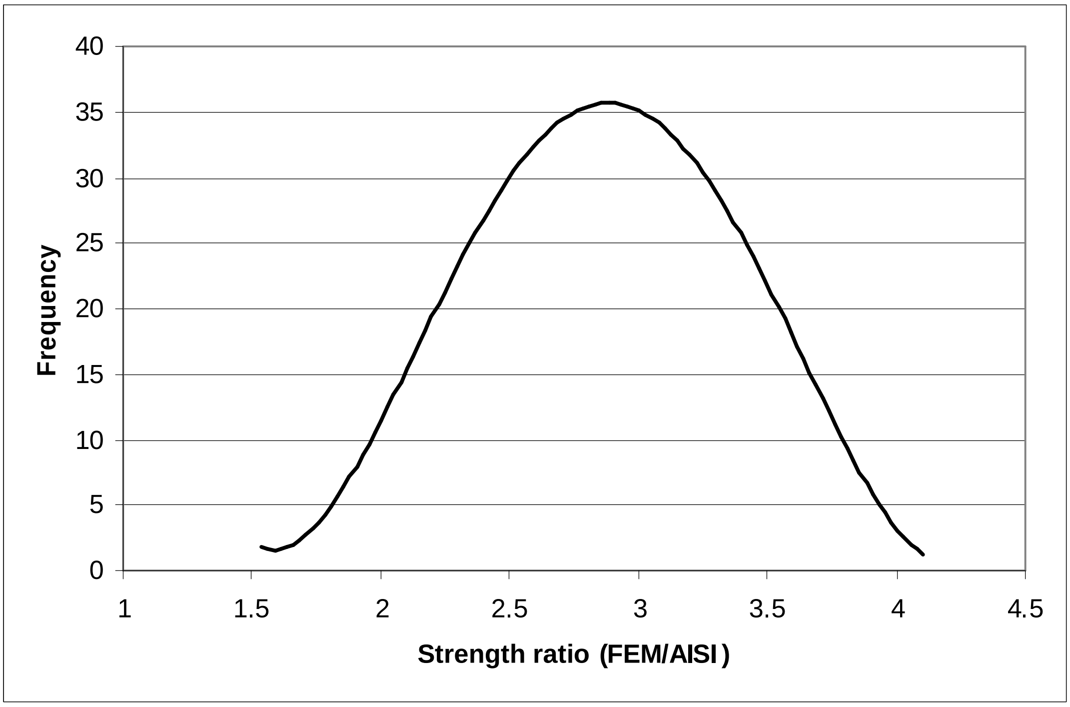

Fig. 4.10 Histogram for the ratio of FEM results to AISI strength of axially loaded members (d/t < 100 for members with tie rods)

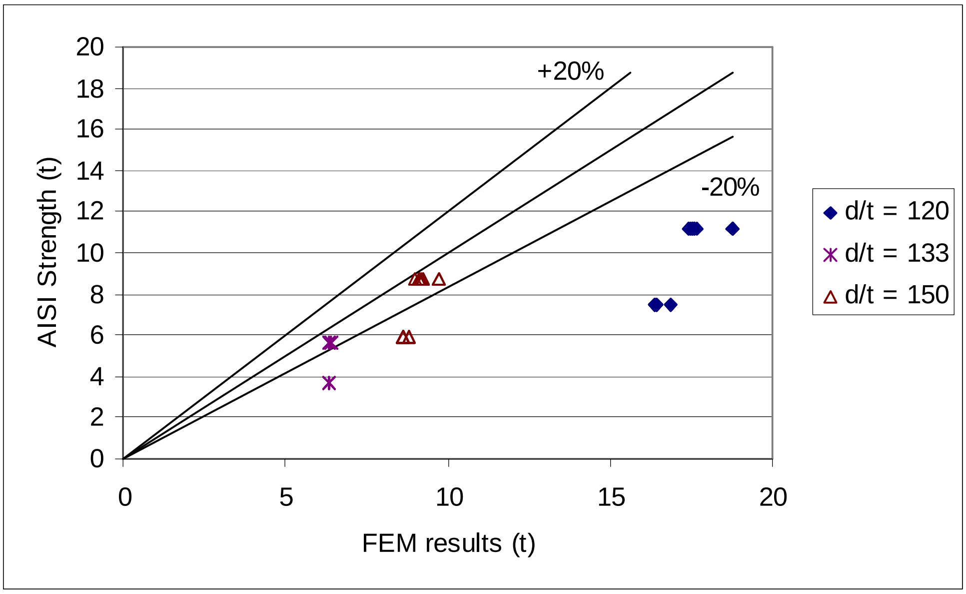

Fig. 4.11 FEM results versus AISI strength of axially loaded members (d/t > 100 for members with tie rods)

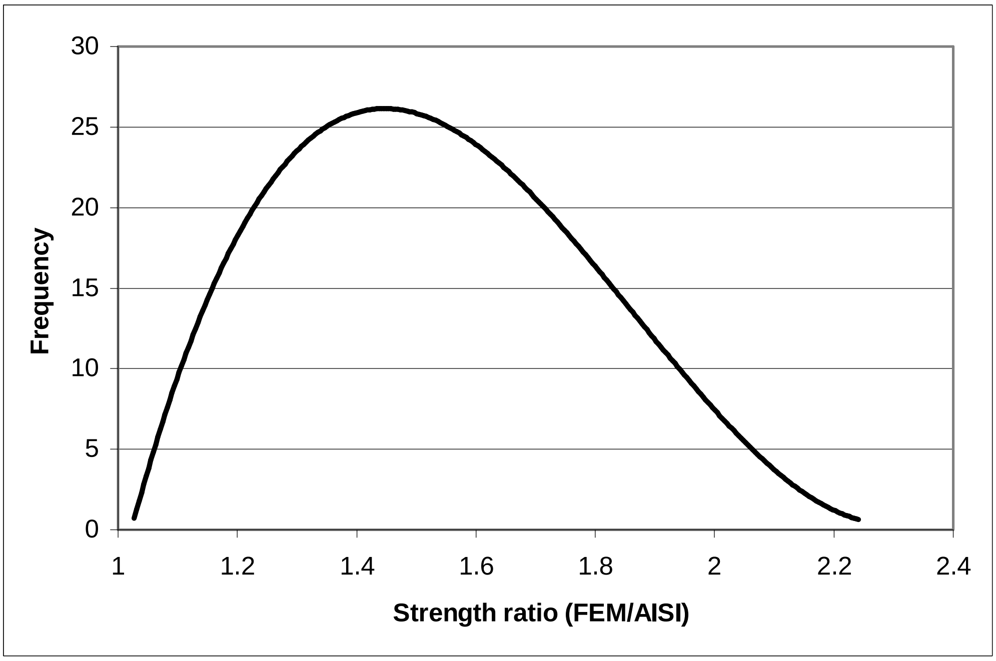

Fig. 4.12 Histogram for the ratio of FEM results to AISI strength of axially loaded members (d/t > 100 for members with tie rods)

Figure 4.13 showed the relation ship between the web depth to thickness ratio and the axial strength of members with tie rods according to AISI and finite element Eigen analysis results. As shown in figure the axial resistance of members decreased as the web depth to thickness ratio increased. The accuracy of results also increased as the web depth to thickness ratio increased

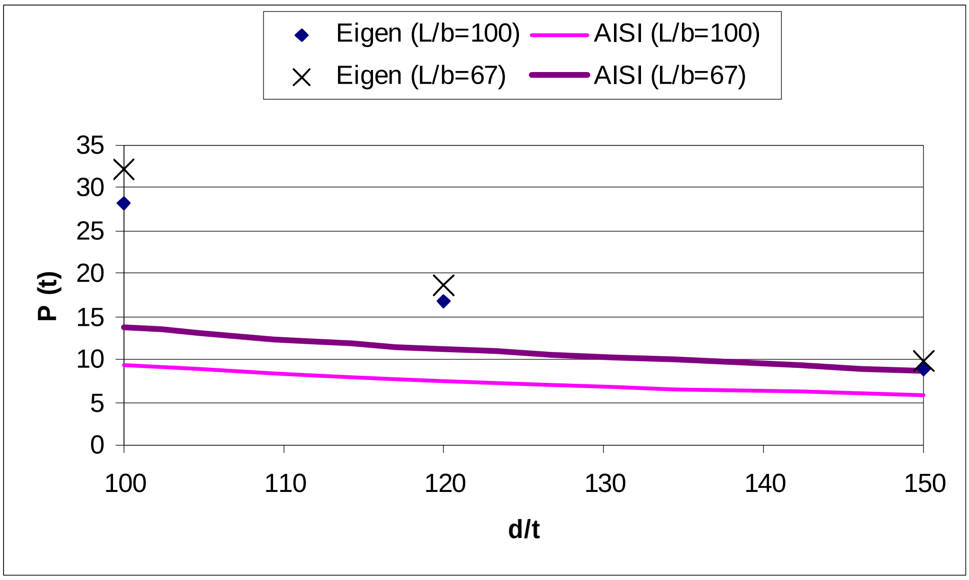

Fig. 4.13 FEM results and AISI strength of axially loaded members with tie rods versus web depth to thickness ratio

As shown in these figures some of the tested members had the same AISI axial strength (i.e. they had the same Y-coordinate), while they had different FEM results. These members had the same cross-section dimensions, so that they had got the same AISI axial strength. Some of other parameters affecting the member's axial strength were not considered in AISI axial strength formulas (like roof lateral and rotational stiffness, etc.).

It also could be observed from these figures that some of tested members had the same finite element analysis results under axial load (i.e. they had the same X-coordinate). This could be attributed to the web local buckling mode which prevails in these members. The local buckling mode is merely affected by web depth to thickness ratio. These members had the same web depth to thickness ratio, but with different flange width, span length, roof lateral and rotational stiffness, etc.

Some of the tested members had the same AISI axial strength, and the same FEM results (i.e. they had the same X-coordinate and Y-coordinate). Points presenting these members coincided with each other and this occurs in members having large web depth to thickness ratio, because these members suffer from web local buckling. Coincident also occurs in members with tie rods rather than members without tie rods, because tie rods may reduce the failure probability due to lateral-torsional buckling.

It could be concluded from the previous figures that the estimation of axial strength of members according to AISI is generally conservative. Only few members of the tested group were non-conservative. AISI was more conservative in the estimation of axial strength of members attached with tie rods. This may be attributed to neglecting the effect of tie rods in the AISI axial strength formulas.

4.5.2 Flexurally Loaded Members

The strength of members obtained from finite element analysis of each member of this group has been compared with the flexural strength of the member calculated from the AISI standard. The flexural strength according to AISI standard was defined as the effective section bending capacity reduced by a reduction factor (refer to (Eq. D6.1.1-1)). This factor depends on the member continuity, cross-section type (C- or Z-cross-section), and the cross-section depth. The effect of lateral and torsional stiffness provided by the sheeting was considered in the provisions by the reduction factors (R). These provisions provide the flexural results of members with tension flange attached to deck or sheeting (i.e. under uplift loads only). AISI gave s formula to estimate the bracing requirement for systems under gravity load with top flange connected to deck or sheathing, while there is no formula to consider the effect of bracing on strength of members undergoing flexural uplift. So that, in this section finite element results of members with tie rods were compared with AISI provisions which did not consider the effect of tie rods.

Comparison between strength of members obtained from finite element analysis and AISI strength of 416 flexurally loaded members was shown in figure 4.14. In this figure finite element results were assigned to X-direction and AISI standard results were assigned to Y-direction. It could be observed from the Figure that 65% of tested members gave very conservative values. About 13% of members of this group gave conservative values with a decrease of less than 20%, and about 11% gave non-conservative values with increase of less than 20%. It is evident that only 14% of the results lie inside the 20% confidence envelopes, while 11% of tested members lie in the very non-conservative zone.

Members of this group have been divided into four subgroups based on the presence or absence of tie rods and the flange width to thickness ratio (b/t). In each of the following figures finite element results were assigned to X-direction and AISI standard results were assigned to Y-direction. Table 4.7 showed some statistic factors for the ratio of FEM results to AISI strength of flexurally loaded members of these subgroups.

Results of 128 members without tie rods having flange width to thickness ratio of less than or equal to 30 were presented in Figure 4.15. It could be observed from the figure that 23% of tested members gave very conservative values. About 18% of members of this group gave conservative values with a decrease of less than 20%, and about 25% gave non-conservative values with increase of less than 20%. It is evident that only 43% of the results lie inside the 20% confidence envelope. About 34% of tested members lie in the very non-conservative zone.

Table 4.7 the ratio of FEM results to AISI strength of flexurally loaded members

M/Mn		**Maximum**	**Minimum**	**Average**	**S.D**	**Correlation**
Without Tie rods	b/t < 30	1.33	0.55	1.02	0.361	0.638
	b/t > 30	1.57	0.81	1.22	0.335	0.797
With Tie rods	b/t < 30	1.90	1.24	1.62	0.212	0.935
	b/t > 30	1.72	1.11	1.46	0.162	0.970

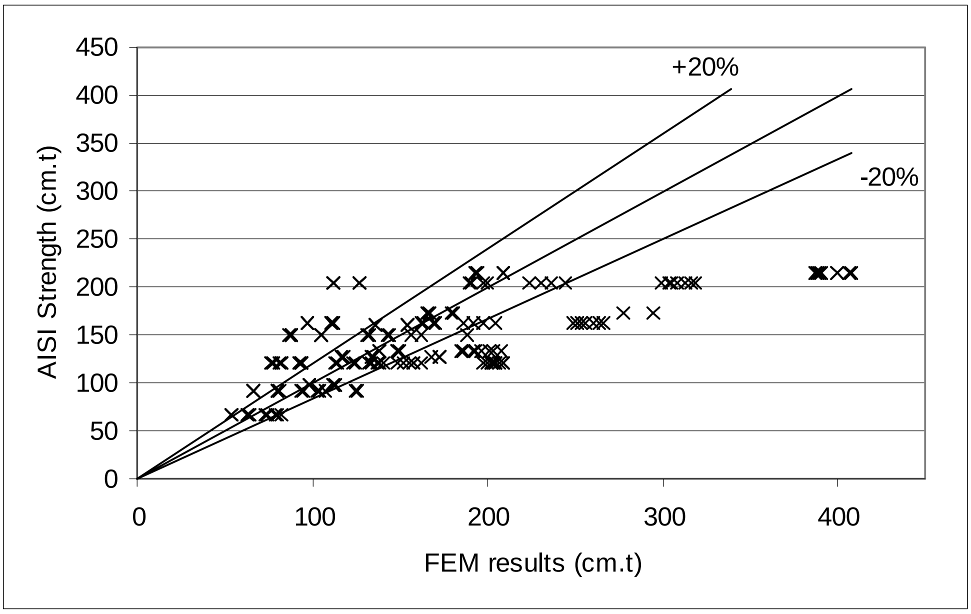

Fig. 4.14 FEM results versus AISI strength of flexurally loaded members

Histogram for the ratio of finite element analysis results under flexural load to AISI flexural strength of members with flange width to thickness ratios of less than or equal to 30 was shown in figure 4.16. It could be observed from this Figure that the ratio of finite element analysis results under flexural load to AISI flexural strength was in the range of (0.548: 1.33) with an average value of (1.02). This subgroup had smaller standard deviation of (0.361) and weak correlation (correlation factor = 0.638).

Results of 80 members without tie rods having flange width to thickness ratios more than 30 were presented in figure 4.17. As shown in the figure 47% of tested members gave very conservative values. About 34% of members of this group gave conservative values with a decrease of less than 20%, and about 19% gave non-conservative values with increase of less than 20%. It could be observed that 53% of the results lie inside the 20% confidence envelopes, none of tested members lie in the very non-conservative zone.

Histogram for the ratio of finite element analysis results under flexural load to AISI flexural strength of members with flange width to thickness ratio of more than 30 was shown in Figure 4.18. It could be observed from this Figure that the ratio of finite element analysis results under flexural load to AISI flexural strength ratio was in the range of (0.812: 1.57) with an average value of (1.22). This subgroup had smaller standard deviation of (0.335) and better correlation (correlation factor = 0.80).

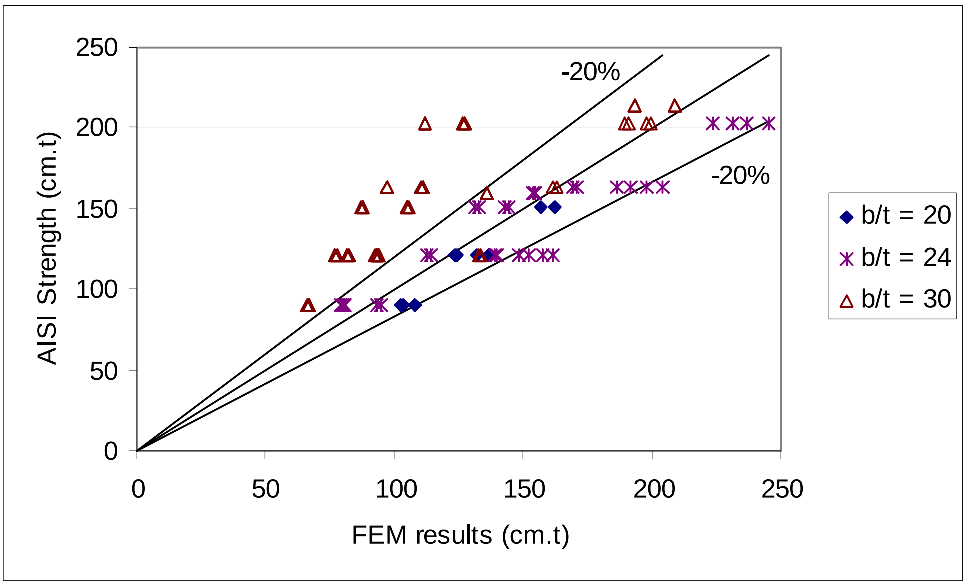

Fig. 4.15 FEM results versus AISI strength of flexurally loaded member (b/t < 30)

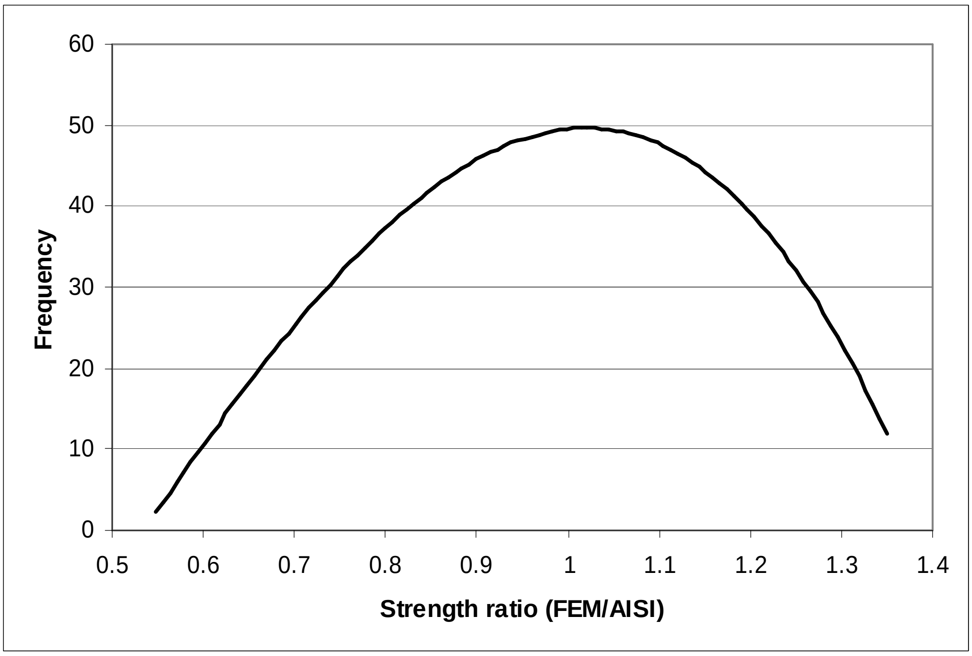

Fig. 4.16 Histogram for the ratio of FEM results to AISI strength of flexurally loaded member (b/t < 30)

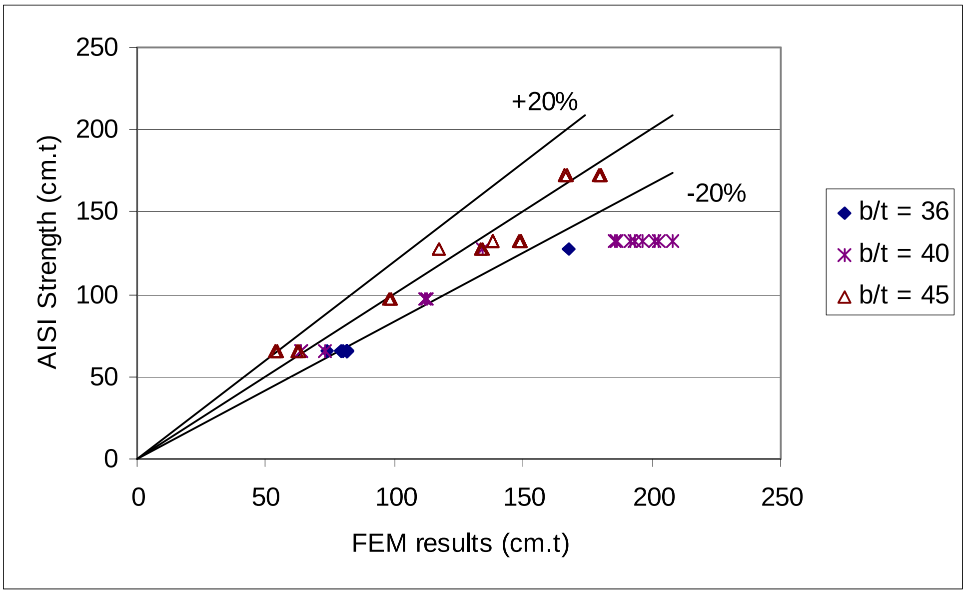

Fig. 4.17 FEM results versus AISI strength of flexurally loaded members (b/t > 30)

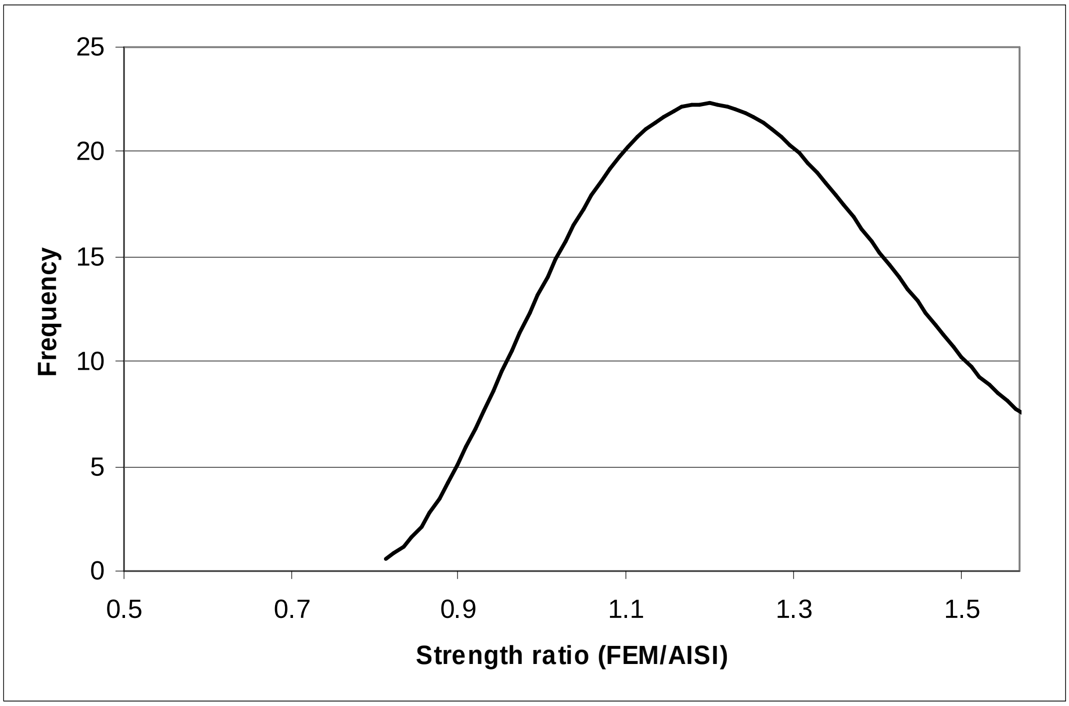

Fig. 4.18 Histogram for the ratio of FEM results to AISI strength of flexurally loaded members (b/t > 30)

Figure 4.19 showed the relationship between the flange width to thickness ratio and the flexural strength of members according to AISI and finite element Eigen analysis results. As shown in figure the flexural resistance of members decreased as the flange width to thickness ratio increased. The accuracy of results also increased as the flange width to thickness ratio increased

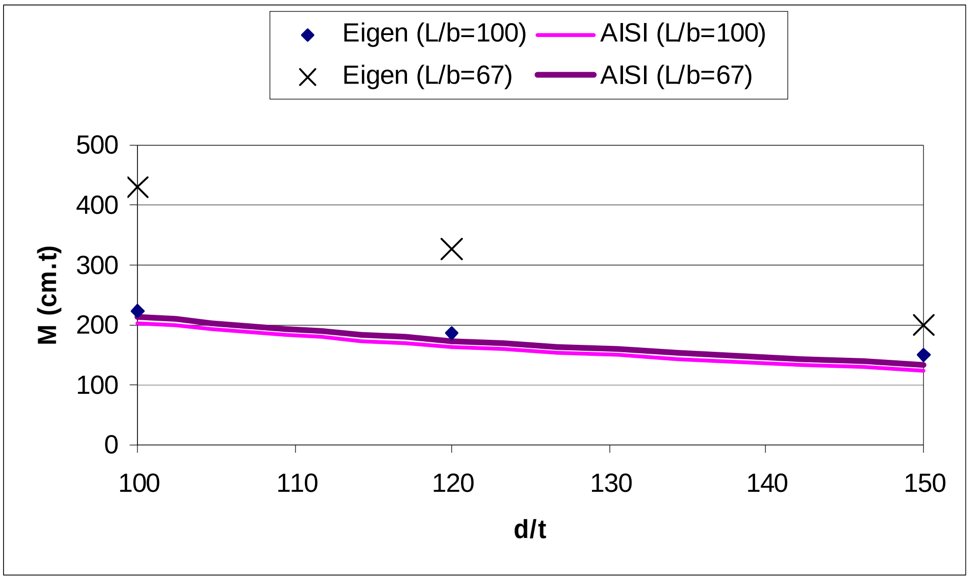

Fig. 4.19 FEM results and AISI strength of flexurally loaded members versus flange width to thickness ratio

Results of 128 members with tie rods having flange width to thickness ratio of less than or equal to 30 were presented in figure 4.20. As shown in the figure all of the members of these subgroups lie in the conservative zone.

Histogram for the ratio of finite element analysis results under flexural load to AISI flexural strength of member with flange width to thickness ratio of less than or equal to 30 was shown in figure 4.21. It could be observed from this Figure that the ratio of finite element analysis results under flexural load to AISI flexural strength ratio was in the range of (1.25 – 1.90) with an average value of (1.62). This subgroup had smaller standard deviation of (0.212) and strong correlation (correlation factor = 0.935).

Results of 80 members with tie rods having flange width to thickness ratios more than 30 were presented in figure 4.22. It could be observed from this figure that 95% of tested members gave very conservative values. About 5% of members of this group gave conservative values with decrease of less than 20%, and none gave non-conservative values.

Histogram for the ratio of finite element analysis results under flexural load to AISI flexural strength of members with flange width to thickness ratios of more than 30 was shown in Figure 4.23. It could be observed from this figure that the ratio of finite element analysis results under flexural load to AISI flexural strength ratio was in the range of (1.12 – 1.72) with an average value of (1.46). This subgroup had smaller standard deviation of (0.162) and very strong correlation (correlation factor = 0.97).

Figure 4.24 showed the relation ship between the flange width to thickness ratio and the flexural strength of members with tie rods according to AISI and finite element Eigen analysis results. As shown in figure the flexural resistance of members decreased as the flange width to thickness ratio increased. The accuracy of results also increased as the flange width to thickness ratio increased

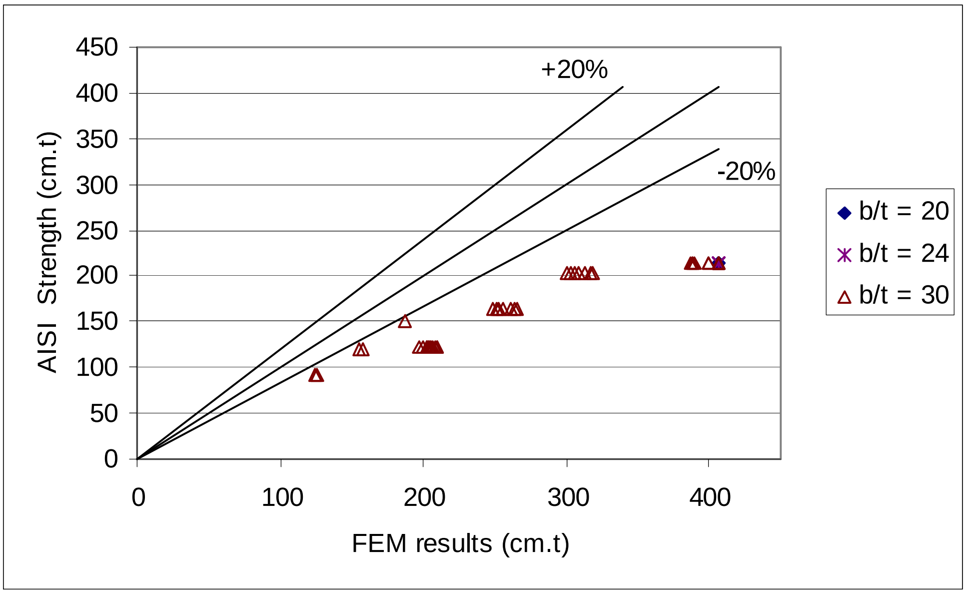

Fig. 4.20 FEM results versus AISI strength of flexurally loaded members (b/t < 30 for members with tie rods)

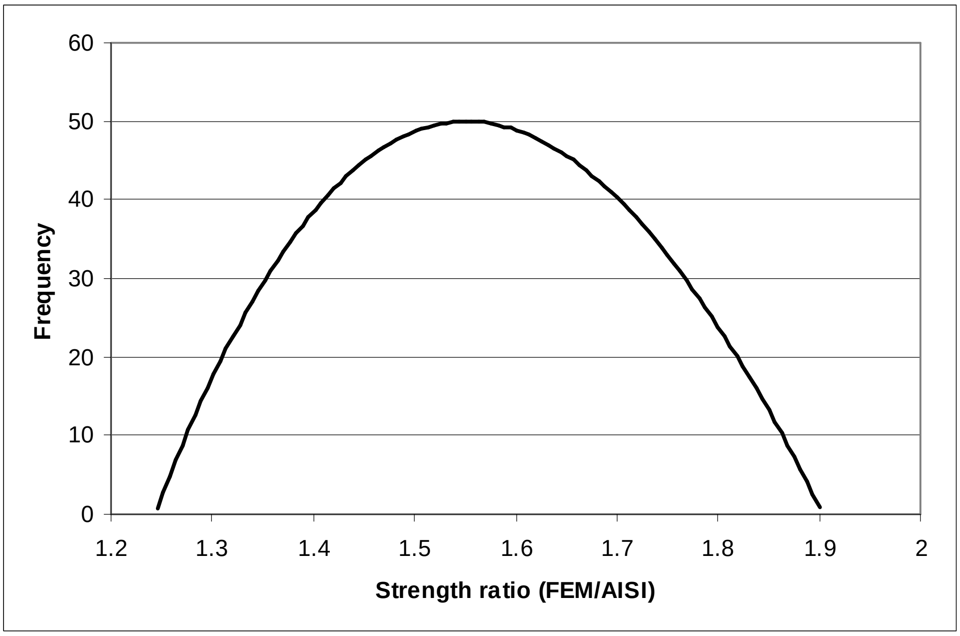

Fig. 4.21 Histogram for the ratio of FEM results to AISI strength of flexurally loaded members (b/t < 30 for members with tie rods)

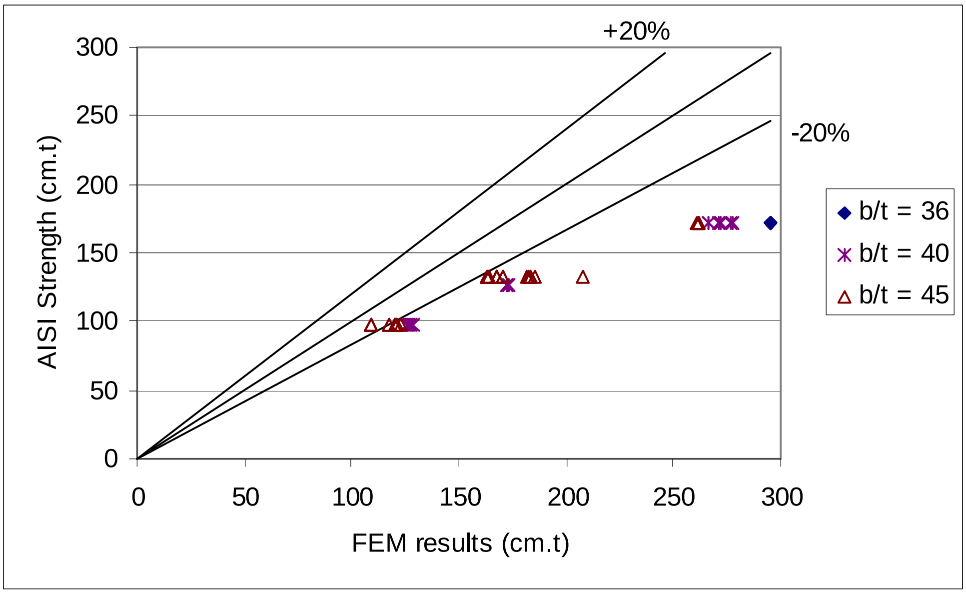

Fig. 4.22 FEM results versus AISI strength of flexurally loaded members (b/t > 30 for members with tie rods)

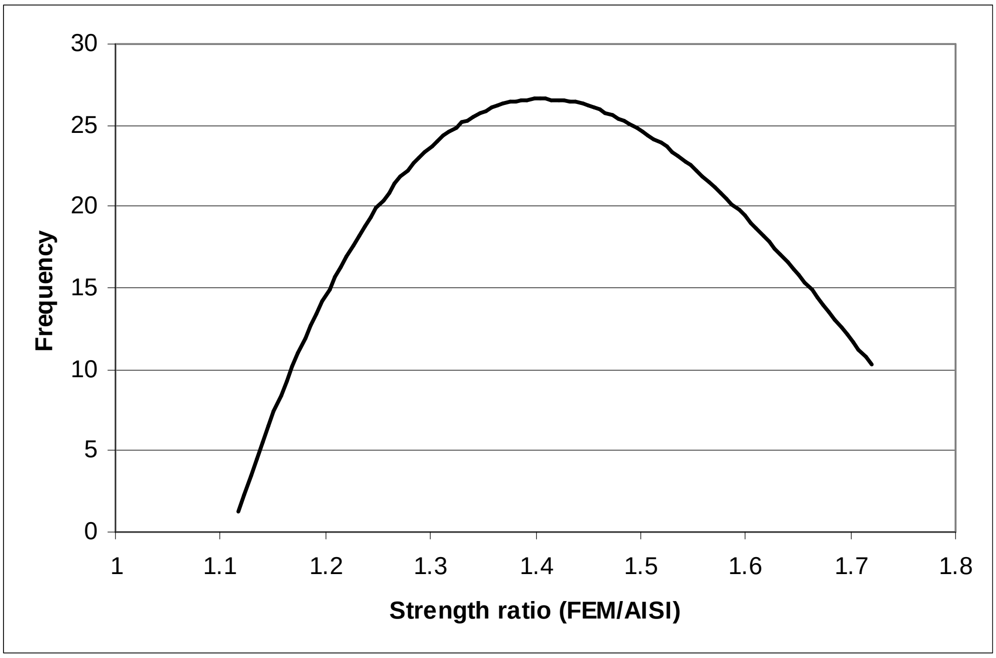

Fig. 4.23 Histogram for the ratio of FEM results to AISI strength of flexurally loaded members (b/t > 30 for members with tie rods)

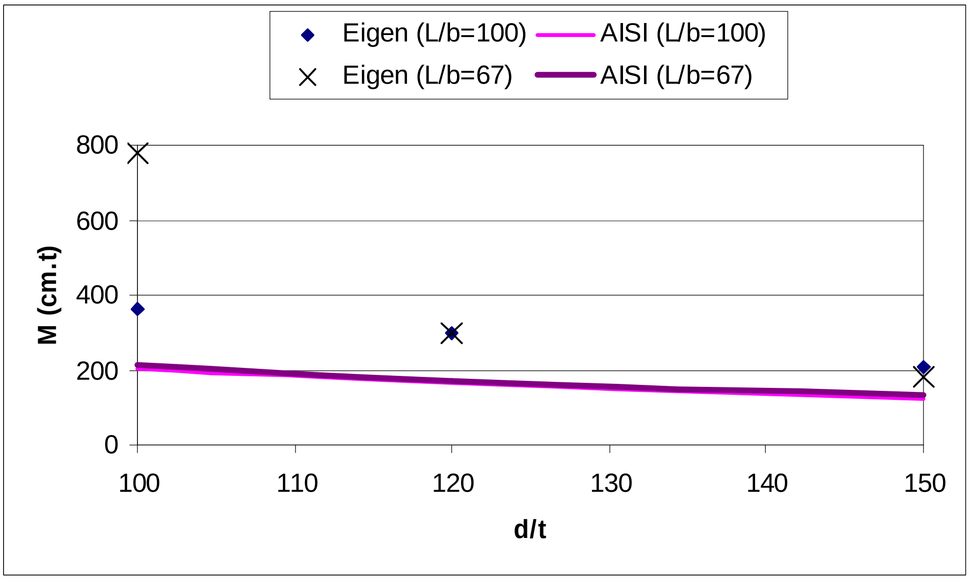

Fig. 4.24 FEM results and AISI strength of flexurally loaded members with tie rods versus flange width to thickness ratio

It could be concluded from the previous figures that the estimation of flexural strength of members according to AISI is generally conservative. Only few members of the tested group were non-conservative. AISI was more conservative in the estimation of flexural strength of members attached with tie rods. This may be attributed to neglecting of the effect of tie rods in the AISI flexural strength formulas for purlins having one flange through fastened to deck or sheeting.

As shown in these figures some of the tested members had the same AISI flexural strength (i.e. they had the same Y-coordinate), while they had different FEM results. These members had the same cross-section dimensions, so that they had the same AISI flexural strength. Some of the other parameters affecting the member flexural strength (like member span length and effect of tie rods) were not considered in AISI flexural strength formulas.

4.6 Finite Element versus Eurocode3

A comparison between the strength of members obtained from finite element analysis of members and the nominal strength of members according to AISI standard Eurocode3 standard (Design of steel structures (part 1.3) cold formed thin gauge members and sheeting) has been performed.

It should be also emphasized that, the utilized finite element analysis in this section is an Eigen value type analysis; therefore the obtained critical buckling load could be higher than the yield load. In some tests the finite element buckling load was greater than 70% of the material yield strength. In these cases, the finite element buckling load will provide a misleading failure load, because these members will actually fail due to material yielding. Buckling will nearly have no effect on the failure of these members. On the other hand, when the ultimate resistance is governed by the elastic stability, the obtained critical buckling load will reasonably represent the failure load. Accordingly, the tests of critical loads higher than the yield strength will be omitted from the following comparison.

4.6.1 Axially Loaded Members

The strength of members obtained from finite element analysis of each member of this group has been compared with the axial strength of the member calculated from the Eurocode3 standard. The axial strength according to Eurocode3 standard was the least of the two values. The first was the axial strength of member based on the actual stress. The second value was the axial strength of member considering the stability of the free flange in compression and its effect on axial strength.

Comparison between strength of members obtained from finite element analysis and Eurocode3 strength of 416 axially loaded members was shown in figure 4.25. In this Figure finite element results were assigned to X-direction and Eurocode3 standard results were assigned to Y-direction. It could be observed from the figure that 47% of tested members gave very conservative values. About 11% of members of this group gave conservative values with a decrease of less than 20%, and about 19% gave non-conservative values with increase of less than 20%. It is evident that only 30% of the results lie inside the 20% confidence envelopes, while 23% of tested members lie in the very non-conservative zone.

Members of this group have been divided into four subgroups based on the presence or absence of tie rods and the web depth to thickness ratio (d/t). In each of the following figures finite element results were assigned to X-direction and Eurocode3 standard results were assigned to Y-direction. Table 4.8 showed some statistic factors for the ratio of FEM results to Eurocode3 strength of axially loaded members.

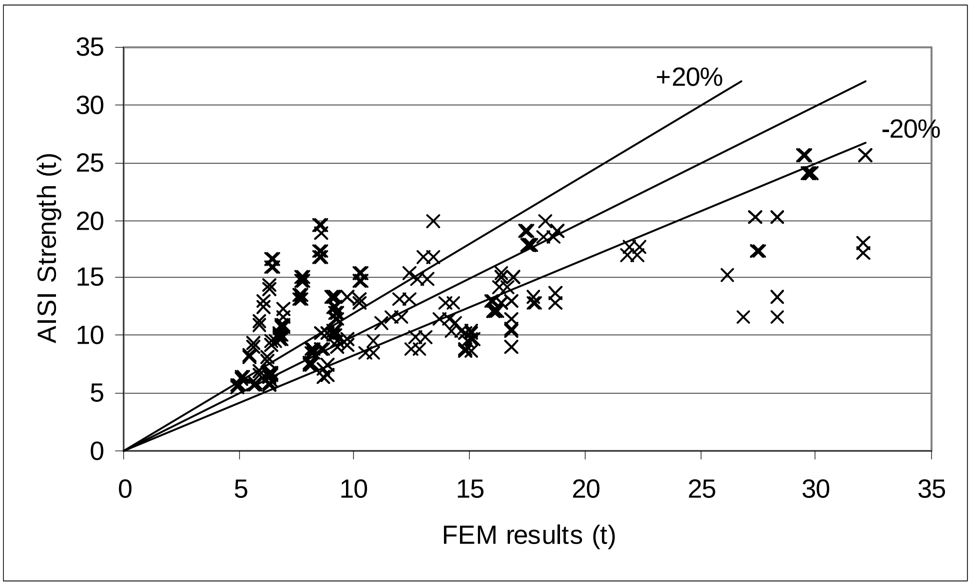

Fig. 4.25 FEM results versus Eurocode3 strength of axially loaded member

Table 4.8 the ratio of FEM results to Eurocode3 strength of axially loaded member

P/Pn		Maximum	Minimum	Average	S.D	Correlation
Without Tie rods	d/t < 100	2.435	0.385	1.036	0.572	0.453
	d/t > 100	1.868	0.667	1.061	0.267	0.802
With Tie rods	d/t < 100	2.482	1.147	1.615	0.304	0.783
	d/t > 100	1.280	0.677	0.964	0.166	0.891

Results of 128 members without tie rods having web depth to thickness ratio of less than or equal to 100 were presented in figure 4.26. It could be observed from the figure that 34% of tested members gave very conservative values. About 8% of members of this group gave conservative values with a decrease of less than 20%, and about 6% gave non-conservative values with an increase of less than 20%. It is evident that only 14% of the results lie inside the 20% confidence envelopes, but 52% of tested members lie in the very non-conservative zone.

Histogram for the ratio of FEM results to Eurocode3 strength of axially loaded members with depth to thickness ratio of less than or equal to 100 was shown in figure 4.27. It could be observed from this figure that the ratio of Finite element analysis results under axial load to Eurocode3 axial strength ratio was in the range of (0.385 – 2.44) with an average value of (1.04). This subgroup had large standard deviation of (0.572) and low correlation (correlation factor = 0.453).

Results of 80 members without tie rods having web depth to thickness ratio of more than 100 were presented in figure 4.28. It could be observed from the Figure that 27% of tested members gave very conservative values. About 18% of members of this group gave conservative values with a decrease of less than 20%, and about 41% gave non-conservative values with an increase of less than 20%. It is evident that only 59% of the results lie inside the 20% confidence envelopes, while 14% of tested members lie in the very non-conservative zone.

Histogram for the ratio of FEM results to Eurocode3 strength of axially loaded members with depth to thickness ratio of more than 100 was shown in Figure 4.29. It could be observed from this figure that the ratio of Finite element analysis results under axial load to Eurocode3 axial strength ratio was in the range of (0.667 –1.868) with an average value of (1.06). This subgroup had smaller standard deviation of (0.267) and better correlation (correlation factor = 0.802).

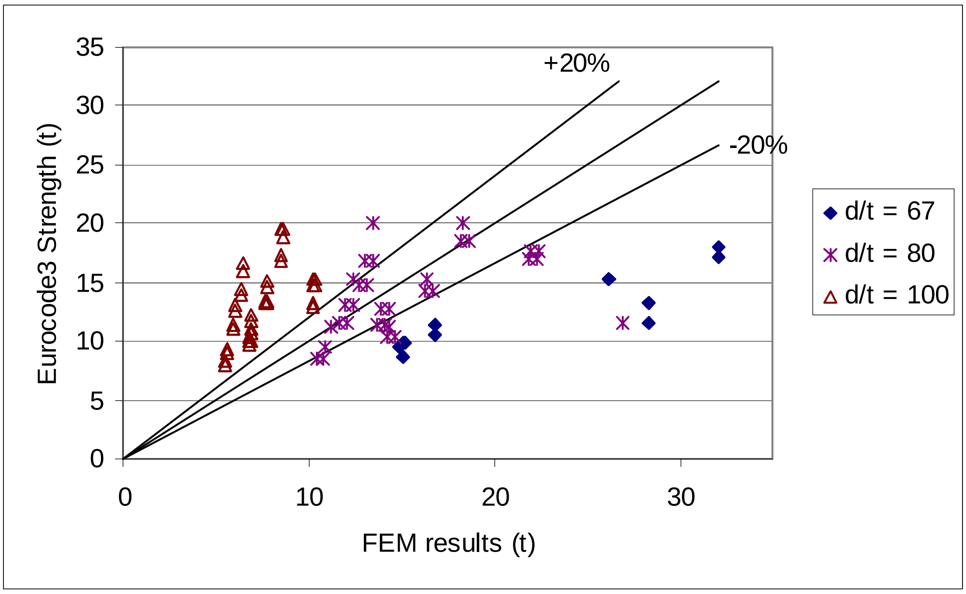

Fig. 4.26 FEM results versus Eurocode3 strength of axially loaded members (d/t < 100)

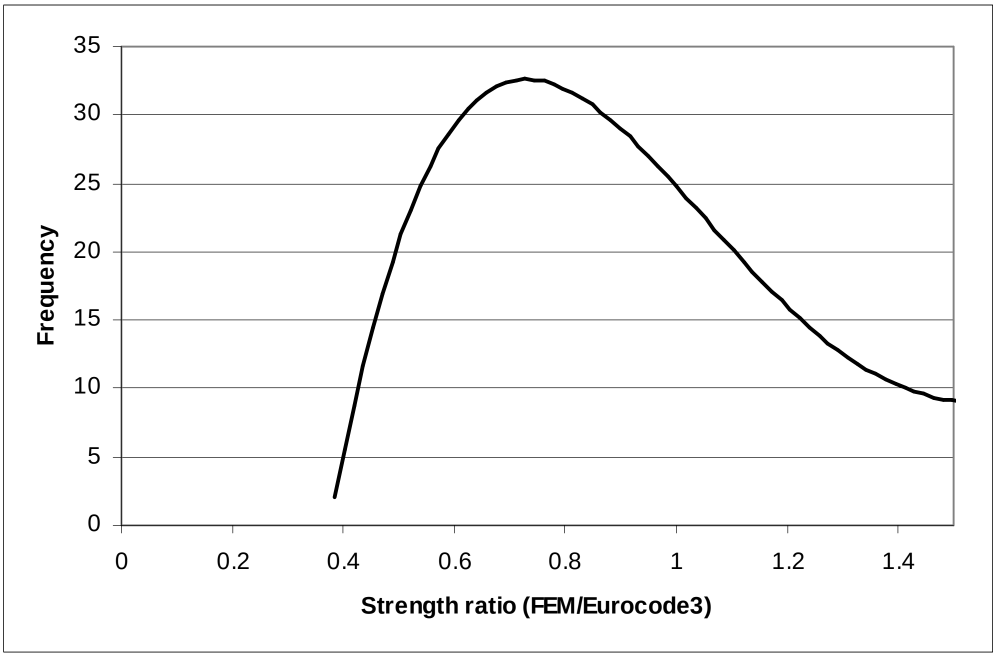

Fig. 4.27 Histogram for the ratio of FEM results to Eurocode3 strength of axially loaded members (d/t < 100)

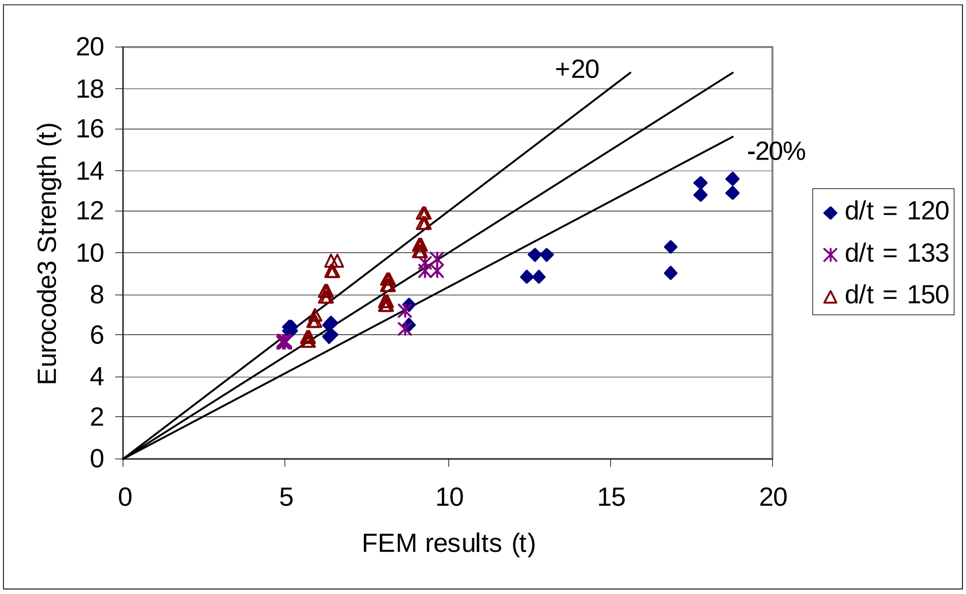

Fig. 4.28 FEM results versus Eurocode3 strength of axially loaded members (d/t > 100)

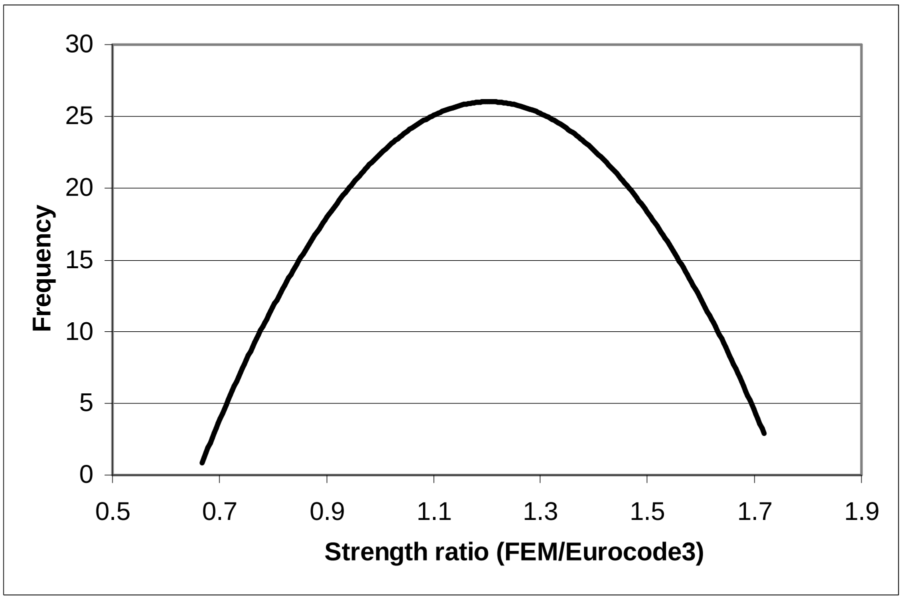

Fig. 4.29 Histogram for the ratio of FEM results to Eurocode3 strength of axially loaded members (d/t > 100)

Figure 4.30 showed the relation ship between the web depth to thickness ratio and the axial strength of members according to AISI and finite element Eigen analysis results. As shown in figure the axial resistance of members decreased as the web depth to thickness ratio increased. The accuracy of results also increased as the web depth to thickness ratio increased.

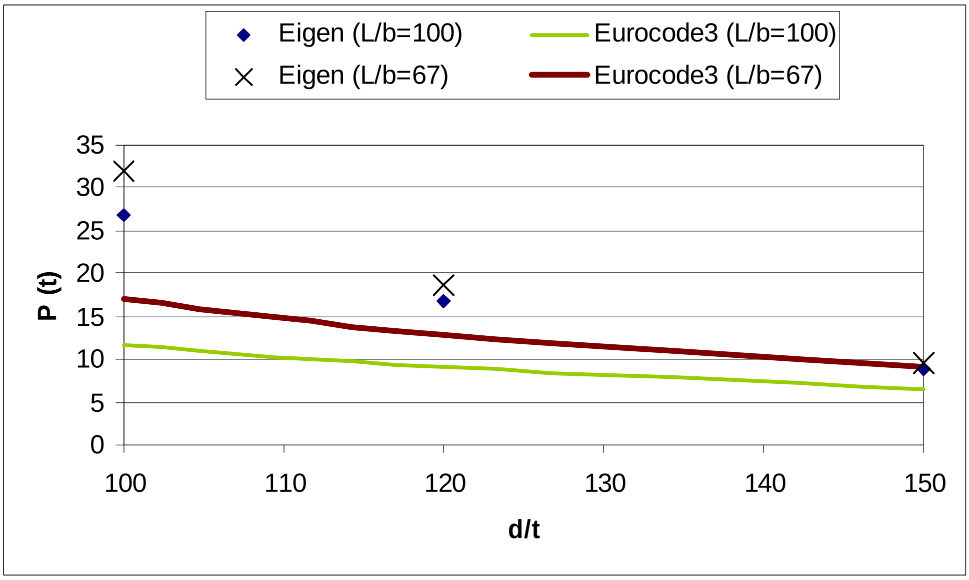

Fig. 4.30 FEM results and AISI strength of axially loaded members versus web depth to thickness ratio

Results of 128 members with tie rods having web depth to thickness ratio of less than or equal to 100 were presented in figure 4.31. It could be observed from this Figure that 97% of tested members gave very conservative values. About 3% of members of this group gave conservative values with decrease of less than 20%, and none gave non-conservative values.

Histogram for the ratio of FEM results to Eurocode3 strength of axially loaded members with depth to thickness ratio of less than or equal to 100 was shown in Figure 4.32. It could be observed from this Figure that the ratio of Finite element analysis results under axial load to Eurocode3 axial strength ratio was in the range of (1.15 – 2.48) with an average value of (1.62). This subgroup had moderate standard deviation of (0.304) and medium correlation (correlation factor = 0.783).

Results of 80 members with tie rods having web depth to thickness ratio more than 100 were presented in figure 4.33. It could be observed from the figure that 10% of tested members gave very conservative values. About 20% of members of this group gave conservative values with a decrease of less than 20%, and about 50% gave non-conservative values with increase of less than 20%. It is evident that only 70% of the results lie inside the 20% confidence envelopes, while 20% of tested members lie in the very non-conservative zone.

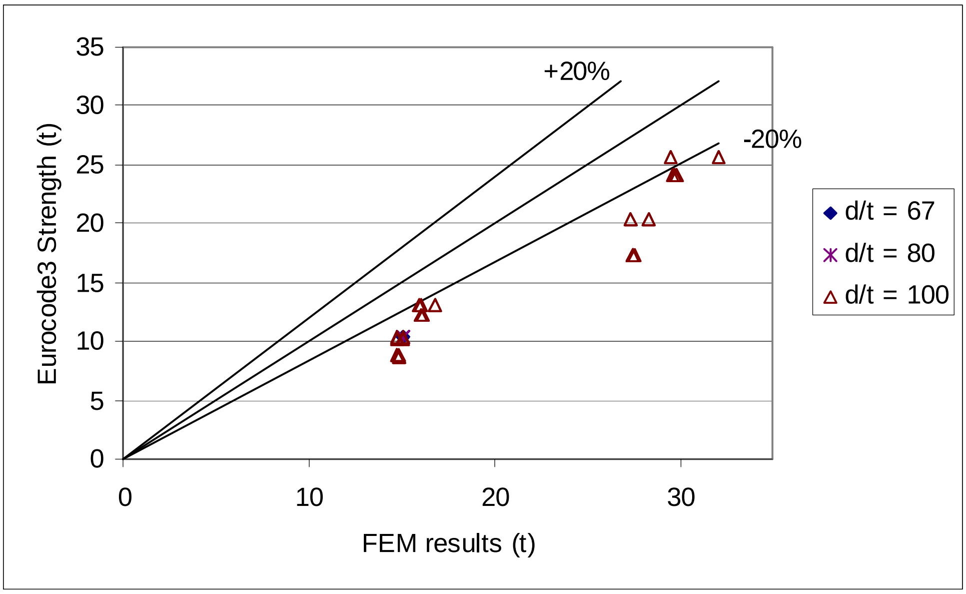

Fig. 4.31 FEM results versus Eurocode3 strength of axially loaded members (d/t < 100 for members with tie rods)

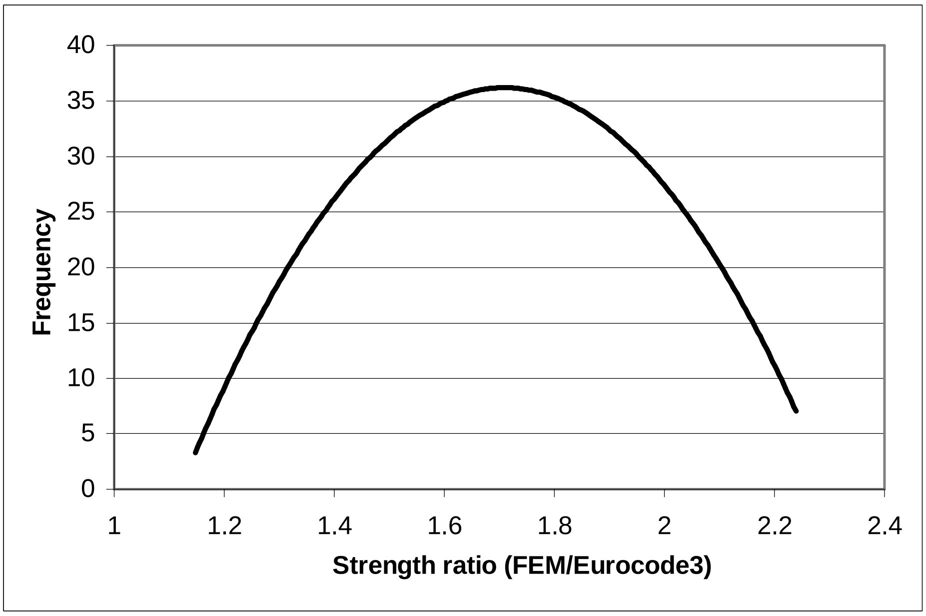

Fig. 4.32 Histogram for the ratio of FEM results to Eurocode3 strength of axially loaded members (d/t < 100 for members with tie rods)

Histogram for the ratio of FEM results to Eurocode3 strength of axially loaded members with depth to thickness ratio more than 100 was shown in figure 4.34. It could be observed from this Figure that the ratio of Finite element analysis results under axial load to Eurocode3 axial strength ratio was in the range of (0.68 – 1.28) with an average value of (0.964). These subgroups had very small standard deviation of (0.166) and better correlation factor of (0.891).

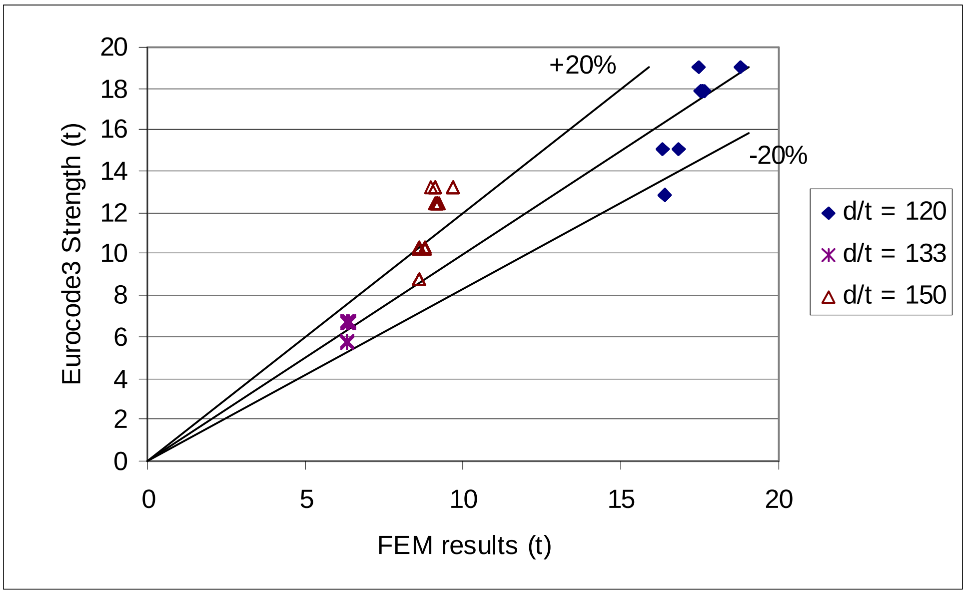

Fig. 4.33 FEM results versus Eurocode3 strength of axially loaded members (d/t > 100 for members with tie rods)

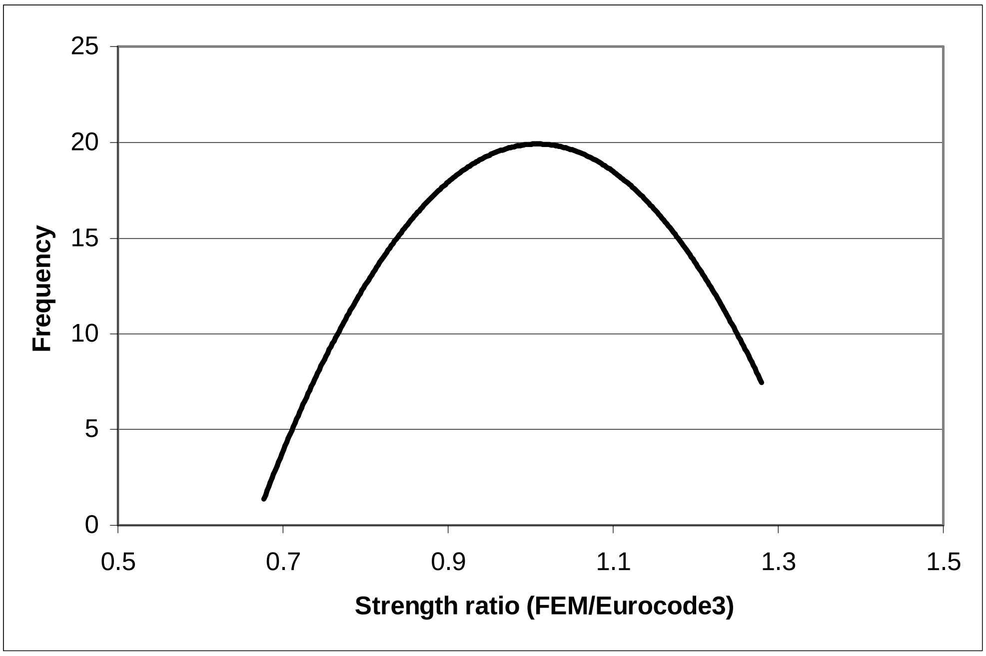

Fig. 4.34 Histogram for the ratio of FEM results to Eurocode3 strength of axially loaded members (d/t > 100 for members with tie rods)

Figure 4.35 showed the relation ship between the web depth to thickness ratio and the axial strength of members with tie rods according to AISI and finite element Eigen analysis results. As shown in figure the axial resistance of members decreased as the web depth to thickness ratio increased. The accuracy of results also increased as the web depth to thickness ratio increased.

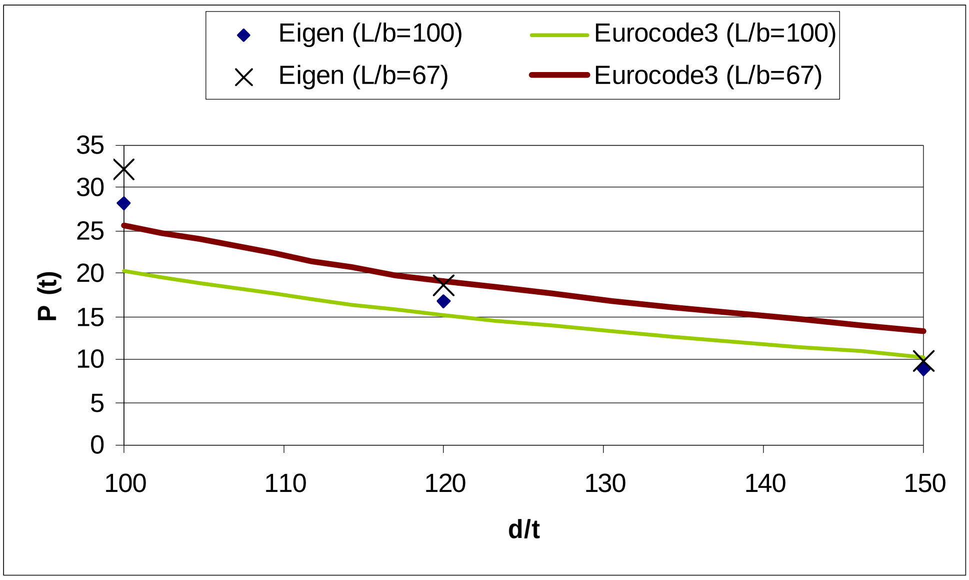

Fig. 4.35 FEM results and AISI strength of axially loaded members with tie rods versus web depth to thickness ratio

As shown in these figures some of the tested members had the same Eurocode3 axial strength (i.e. they had the same Y-coordinate), while they had different FEM results. These members had the same cross-section dimensions, so that in most of these cases they have the same effective area.

It could also be observed from these figures that some of the tested members had the same Finite element analysis results under axial load (i.e. they had the same X-coordinate). This could be attributed to the web local buckling mode which prevails in these members. The local buckling mode is merely affected by web depth to thickness ratio. Its probability increased in cases of members with large web depth to thickness ratio (d/t > 100).

Some of tested members had the same Eurocode3 axial strength, and the same FEM results (i.e. they had the same X-coordinate and Y-coordinate). Points presenting these members coincided with each other. Coincident more occurs in members having large web depth to thickness ratio, because these members suffer from web local buckling. Coincident also occurs in members with tie rods rather than members without tie rods, because tie rods may increase the probability of web local buckling.

It could be concluded from the previous figures that the estimation of axial strength of members according to Eurocode3 generally is less conservative than estimations of the AISI. Some members of the tested group were non-conservative. Eurocode3 was more conservative in the estimation of axial strength of members attached with tie rods. This may be attributed to the consideration of the effect of tie rods in the Eurocode3 axial strength formulas.

4.6.2 Flexurally Loaded Members

The strength of members obtained from finite element analysis of each member of this group have been compared with the flexural strength of the member calculated from the Eurocode3 standard. The flexural strength according to Eurocode3 standard was defined as the most critical value based on two checks. The actual stress check was the first check. The other check was for the stability of the free flange in compression and its effect on the flexural strength of member.

Comparison between strength of members obtained from finite element analysis and Eurocode3 strength of 416 flexurally loaded members was shown in Figure 4.36. In this Figure finite element results were assigned to X-direction and Eurocode3 standard results were assigned to Y-direction. It could be observed from the Figure that 71% of tested members gave very conservative values. About 14% of members of this group gave conservative values with a decrease of less than 20%, and about 15% gave non-conservative values with increase of less than 20%. It is evident that only 29% of the results lie inside the 20% confidence envelopes, while none of tested members lie in the very non-conservative zone. Table 4.9 showed some statistic factors for the ratio of FEM results to Eurocode3 strength of flexurally loaded members of this group.

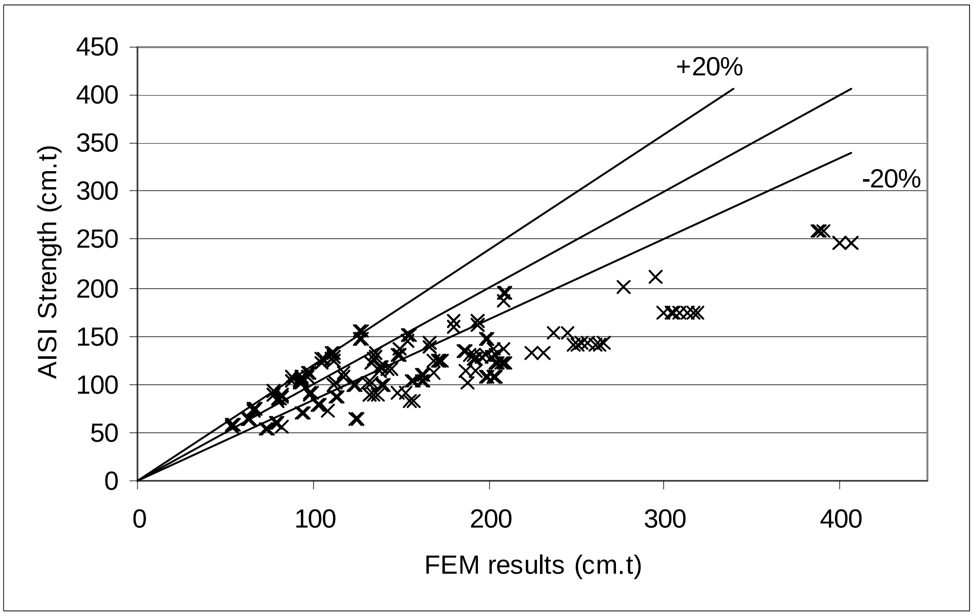

Fig. 4.36 FEM results versus Eurocode3 strength of flexurally loaded member

Table 4.9 the ratio of FEM results to Eurocode3 strength of flexurally loaded member

M/Mn		Maximum	Minimum	Average	S.D	Correlation
Without Tie rods	b/t < 30	1.73	0.81	1.32	0.386	0.787
	b/t > 30	1.57	0.93	1.28	0.358	0.815
With Tie rods	b/t < 30	1.97	1.50	1.78	0.195	0.952
	b/t > 30	1.40	0.99	1.26	0.267	0.926

Results of 128 members without tie rods having flange width to thickness ratio of less than or equal to 30 were presented in figure 4.37. It could be observed from the figure that 50% of tested members gave very conservative values. About 13% of members of this group gave conservative values with a decrease of less than 20%, and about 37% gave non-conservative values with increase of less than 20%. It is evident that only 50% of the results lie inside the 20% confidence envelopes, while 25% of tested members lie in the very non-conservative zone.

Histogram for the ratio of finite element analysis results under flexural load to Eurocode3 flexural strength of member with flange width to thickness ratio of less than or equal to 30 was shown in figure 4.38. It could be observed from this figure that the ratio of finite element analysis results under flexural load to Eurocode3 flexural strength ratio was in the range of (0.81 – 1.73) with an average value of

(1.32). This subgroup had smaller standard deviation of (0.386) and good correlation (correlation factor = 0.787).

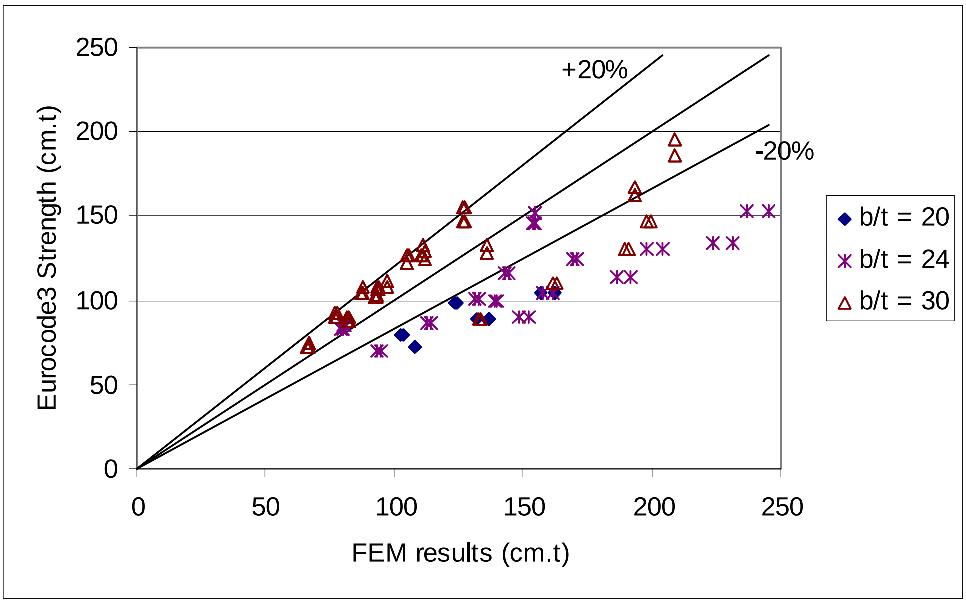

Fig. 4.37 FEM results versus Eurocode3 strength of flexurally loaded members (b/t < 30)

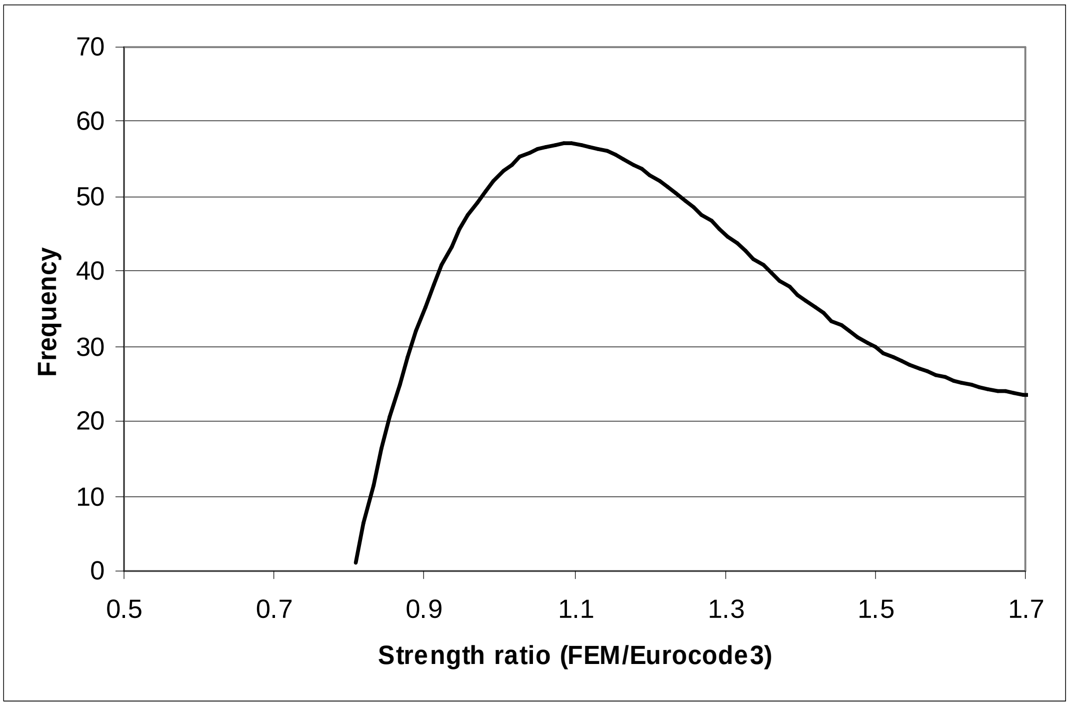

Fig. 4.38 Histogram for the ratio of FEM results to Eurocode3 strength of flexurally loaded members (b/t < 30)

Results of 80 members without tie rods having flange width to thickness ratio more than 30 were presented in figure 4.39. It could be observed from the Figure that 55% of tested members gave very conservative values. About 35% of members of this group gave conservative values with a decrease of less than 20%, and about 10% gave non-conservative values with increase of less than 20%. It is evident that only 45% of the results lie inside the 20% confidence envelopes. All tested members of this subgroup were accepted because none of them lies in the very non-conservative zone.

Histogram for the ratio of finite element analysis results under flexural load to Eurocode3 flexural strength of members with flange width to thickness ratio of more than 30 was shown in figure 4.40. It could be observed from this Figure that the ratio of finite element analysis results under flexural load to Eurocode3 flexural strength ratio was in the range of (0.927 – 1.57) with an average value of (1.28). This subgroup had smaller standard deviation of (0.358) and good correlation (correlation factor = 0.815).

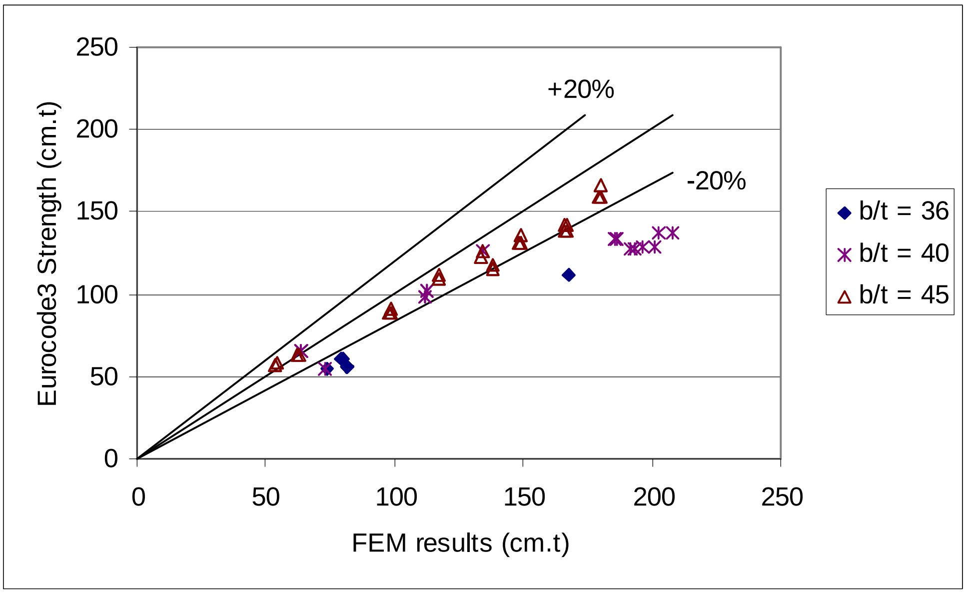

Fig. 4.39 FEM results versus Eurocode3 strength of flexurally loaded members (b/t > 30)

Figure 4.41 showed the relation ship between the flange width to thickness ratio and the flexural strength of members according to AISI and finite element Eigen analysis results. As shown in figure the flexural resistance of members decreased as the flange width to thickness ratio increased. The accuracy of results also increased as the flange width to thickness ratio increased.

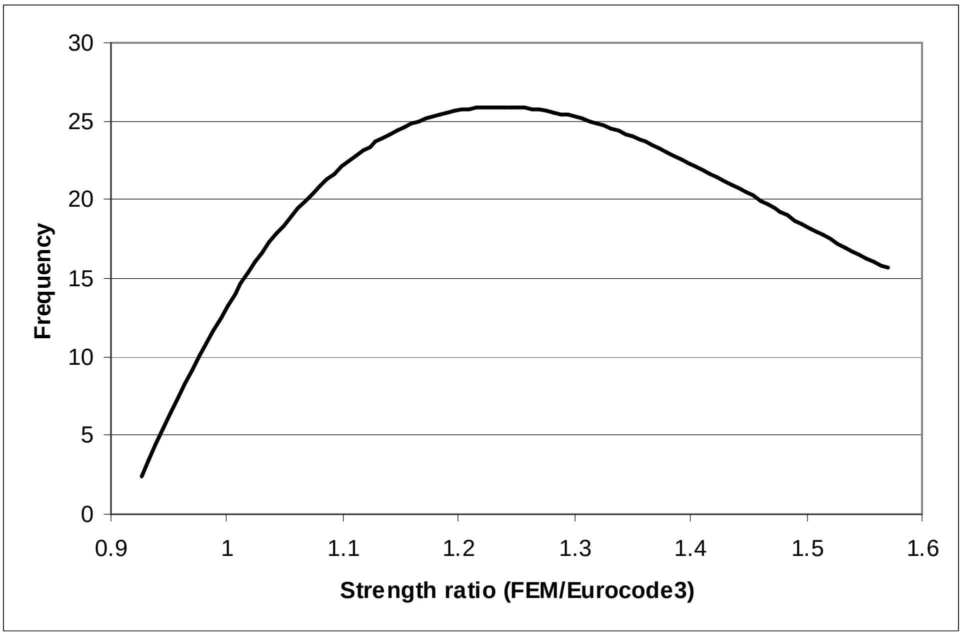

Fig. 4.40 Histogram for the ratio of FEM results to Eurocode3 strength of flexurally loaded members (b/t > 30)

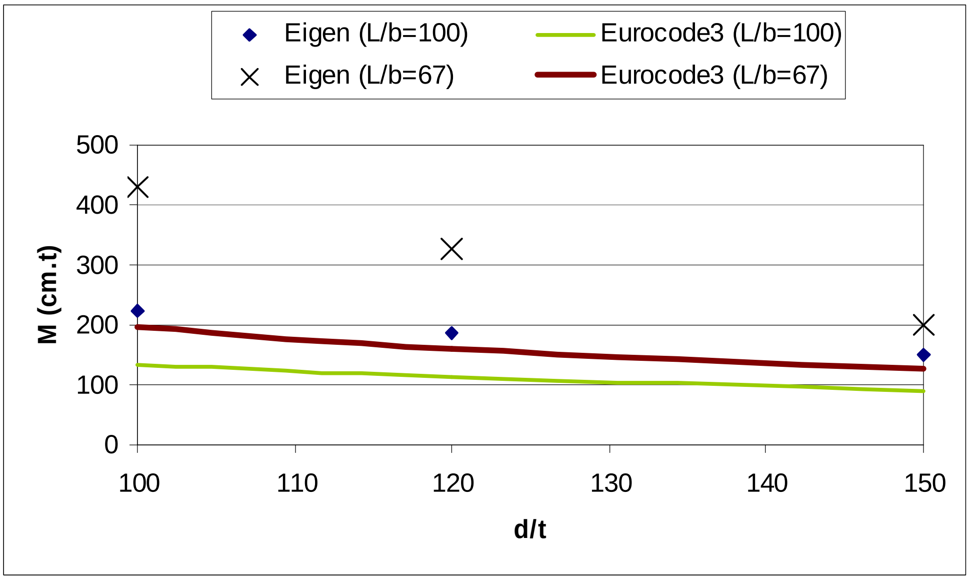

Fig. 4.41 FEM results and AISI strength of flexurally loaded members versus flange width to thickness ratio

Results of 128 members with tie rods having flange width to thickness ratio of less than or equal to 30 were presented in figure 4.42. As shown in the Figure all of the members of these subgroups lie in the conservative zone.

Histogram for the ratio of finite element analysis results under flexural load to Eurocode3 flexural strength of members with flange width to thickness ratio of less than or equal to 30 was shown in figure 4.43. It could be observed from this Figure that the ratio of finite element analysis results under flexural load to Eurocode3 flexural strength ratio was in the range of (1.50 – 1.97) with an average value of (1.78). This subgroup had smaller standard deviation of (0.195) and strong correlation (correlation factor = 0.952).

Results of 80 members with tie rods having flange width to thickness ratio of more than 30 were presented in figure 4.44. It could be observed from the Figure that 76% of tested members gave very conservative values. About 19% of members of this group gave conservative values with a decrease of less than 20%, and about 5% gave non-conservative values with increase of less than 20%. It is evident that only 24% of the results lie inside the 20% confidence envelopes, while none of tested members lie in the very non-conservative zone.

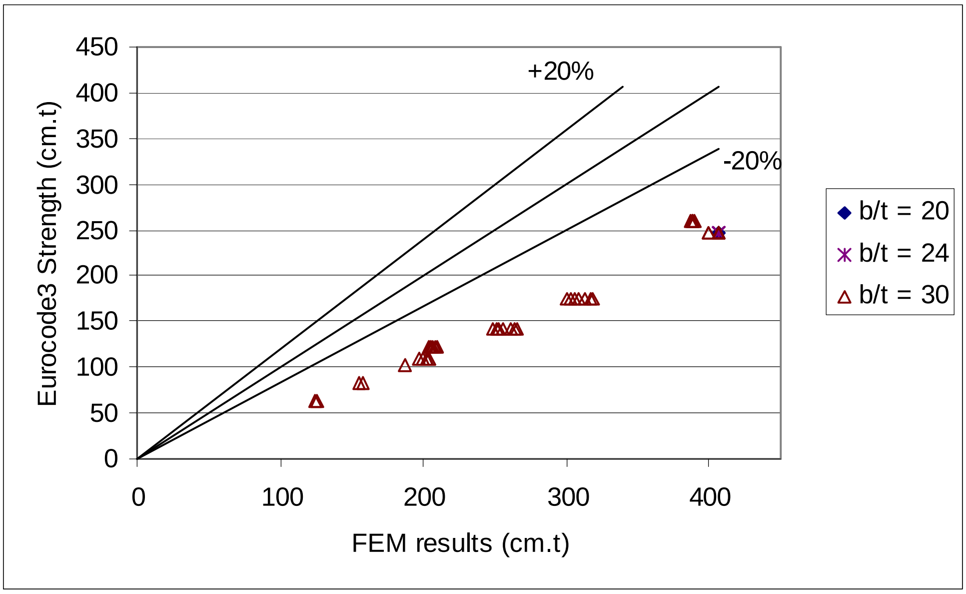

Fig. 4.42 FEM results versus Eurocode3 strength of flexurally loaded members (b/t < 30 for members with tie rods)

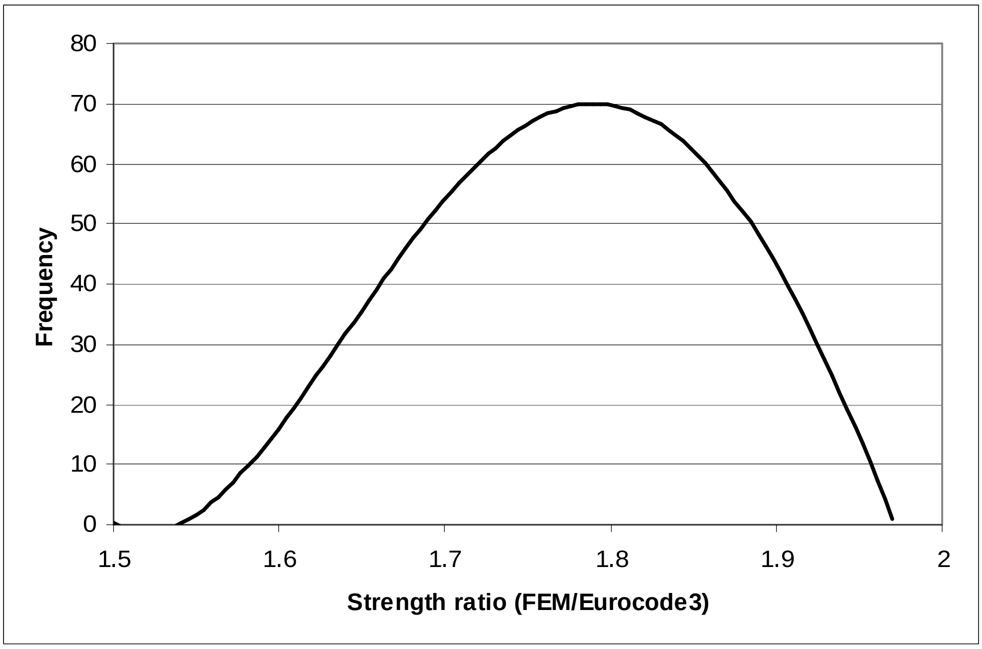

Fig. 4.43 Histogram for the ratio of FEM results to Eurocode3 strength of flexurally loaded members (b/t < 30 for members with tie rods)

Histogram for the ratio of finite element analysis results under flexural load to Eurocode3 flexural strength of member with flange width to thickness ratio of more than 30 was shown in figure 4.45. It could be observed from this Figure that the ratio of finite element analysis results under flexural load to Eurocode3 flexural strength ratio was in the range of (1.0 – 1.4) with an average value of (1.26). This subgroup had smaller standard deviation of (0.267) and strong correlation (correlation factor = 0.926).

Figure 4.46 showed the relation ship between the flange width to thickness ratio and the flexural strength of members with tie rods according to AISI and finite element Eigen analysis results. As shown in figure the flexural resistance of members decreased as the flange width to thickness ratio increased. The accuracy of results also increased as the flange width to thickness ratio increased.

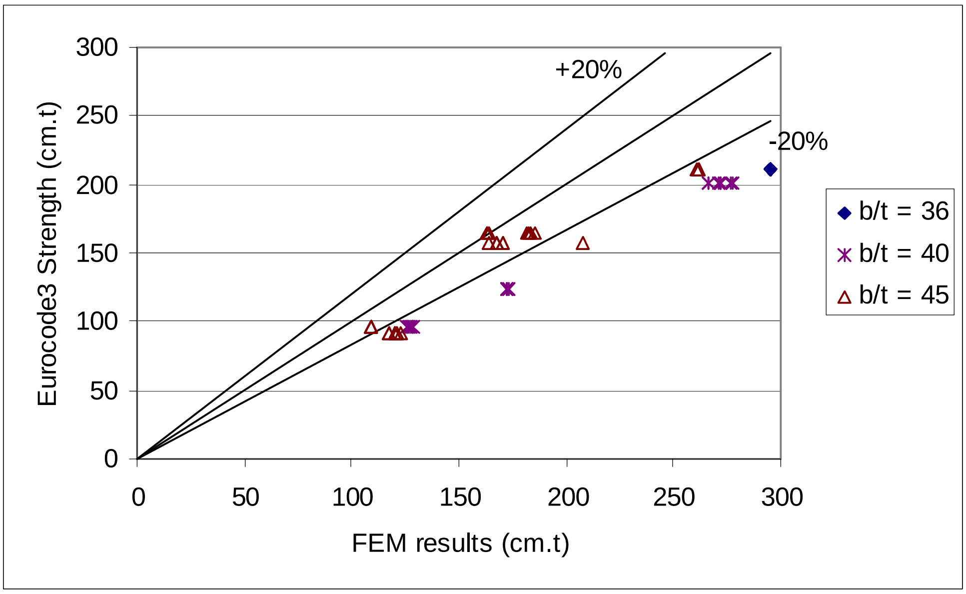

Fig. 4.44 FEM results versus Eurocode3 strength of flexurally loaded members (b/t > 30 for members with tie rods)

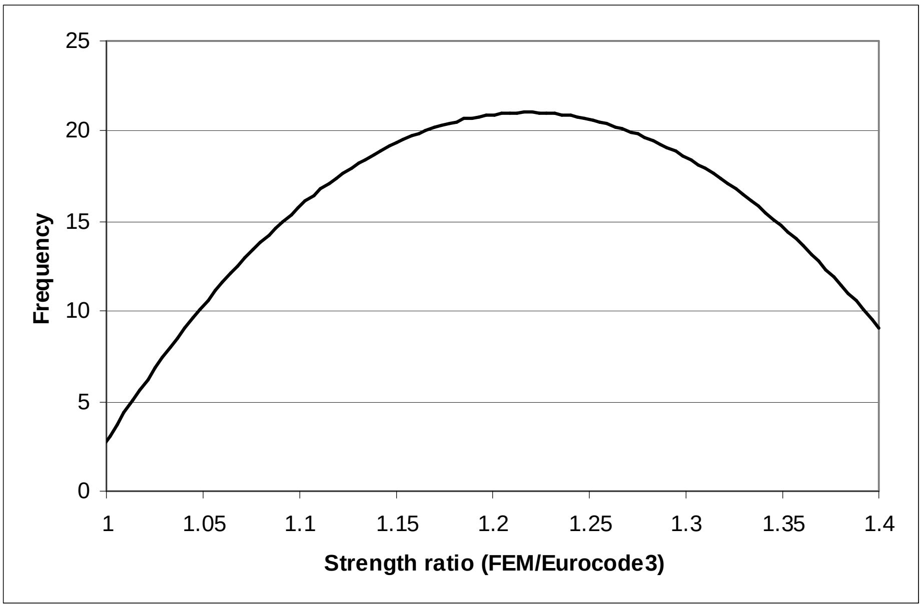

Fig. 4.45 Histogram for the ratio of FEM results to Eurocode3 strength of flexurally loaded members (b/t > 30 for members with tie rods)

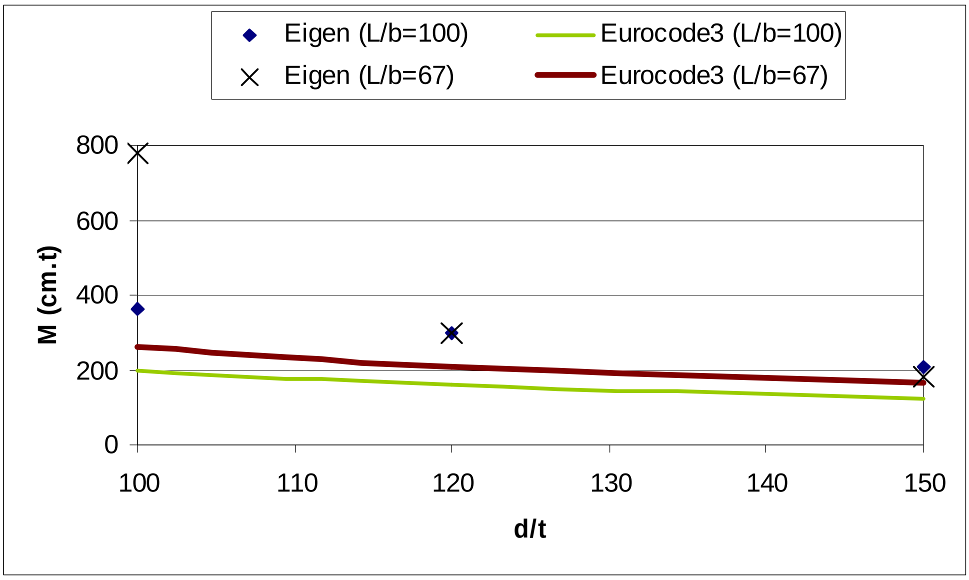

Fig. 4.46 FEM results and AISI strength of flexurally loaded members with tie rods versus flange width to thickness ratio

It could be concluded from the previous figures that estimation of flexural strength of members according to Eurocode3 is generally conservative. Only few members of the tested group were non-conservative. Eurocode3 was more conservative in the estimation of flexural strength of members attached with tie rods. This may be attributed to the estimation of effect of tie rods in the Eurocode3 flexural strength formulas.

It should be considered that the difference between finite element analysis results and the ultimate strength according to AISI or Eurocode3 may be attributed to the difference between the adopted failure criteria by each of them. Finite element analysis in this thesis adopted the Eigen value analysis as the failure criteria. Eigen value analysis gave s the critical buckling load of the member due to local buckling or overall buckling. While design codes define the ultimate strength of the member as the maximum load which the member could carry. This approach allows for stress distribution and post buckling strength.

In the previous figures (in section 4.4 and 4.5) some points lied in the non-conservative zone. The AISI and Eurocode3 strength were greater than the finite element Eigen buckling load. In these members the finite element analysis gave s a value smaller than the actual load that the member could carry. This occurs only if the local buckling is governing the failure of the structural element. The smaller value provided by the finite element analysis correspond to local buckling load, while the design codes considered the stress redistribution over the whole cross-section. The stresses on cross-section elements suffering from local buckling went to the other cross-section elements not suffering from local buckling. The design codes allowed for post buckling strength. So that, stresses on the cross section were redistributed and the member carried load more than the Eigen buckling load.

Some other points lied in the very conservative zone. In these tests the finite element Eigen analysis gave a critical buckling load very greater than the strength gave n by each of AISI or Eurocode3. In this case the Eigen buckling load was greater than the actual load that the member could carry, because the Eigen buckling load (which did not considered the material yield stress) gave a value greater than the yield strength of the member. So that the member failed due to material strength not the buckling strength

4.7 Finite Element Nonlinear Analysis

The results obtained from finite element nonlinear analysis of axially loaded members without tie rods were shown in figure 4.47. This figure also shows the nominal axial strength of tested members according to AISI and Eurocode3. Figure 4.48 presents such comparison for members attached with tie rods. Column heights in these Figures represent the ratio (P/Pc). The load (P) is the axial strength of the member according to nonlinear analysis, AISI, or Eurocode3. The load (Pc) is the Eigen analysis buckling load of the member.

It could be observed from these figures that there is an accepted agreement between Eigen finite element analysis and the nonlinear finite element analysis. Results of nonlinear analysis were very close to Eigen analysis in cases of smaller thickness. Deviation of nonlinear analysis from Eigen analysis increased as the thickness increased. Load-displacement curves of axially loaded members showed in figure 4.49 for axially loaded members without tie rods. Displacement was measured at the junction between the web and bottom flange for mid-span cross-section.

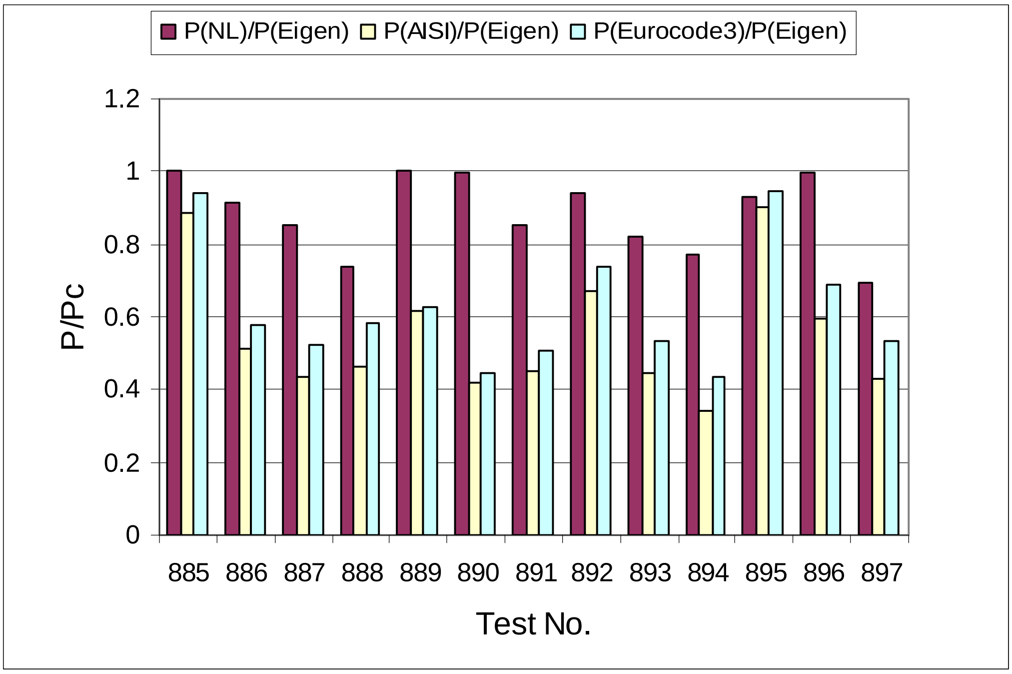

Fig. 4.47 Failure load of axially loaded members without tie rods

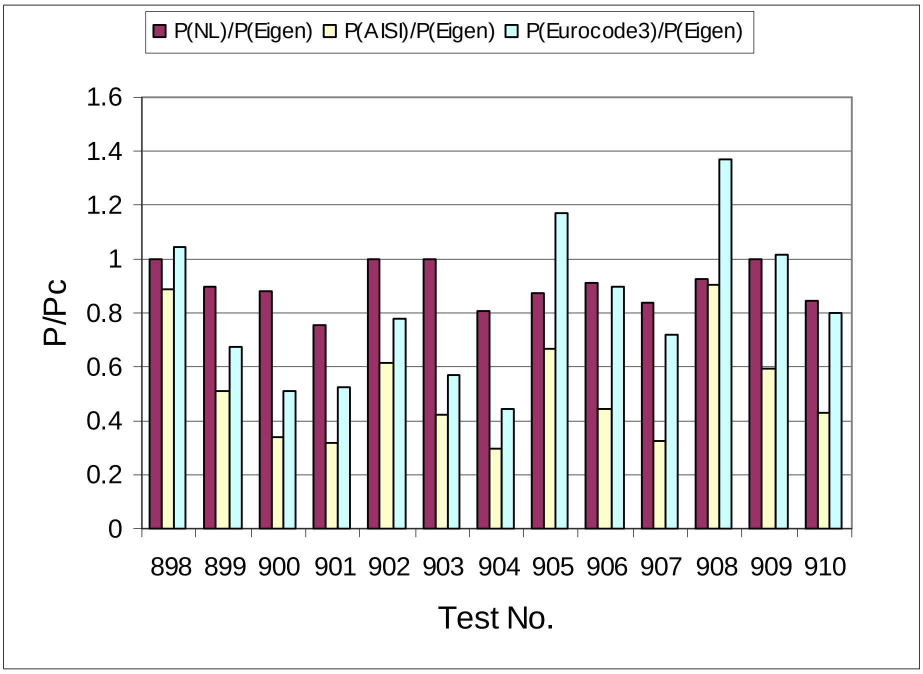

Fig. 4.48Failure load of axially loaded members with tie rods

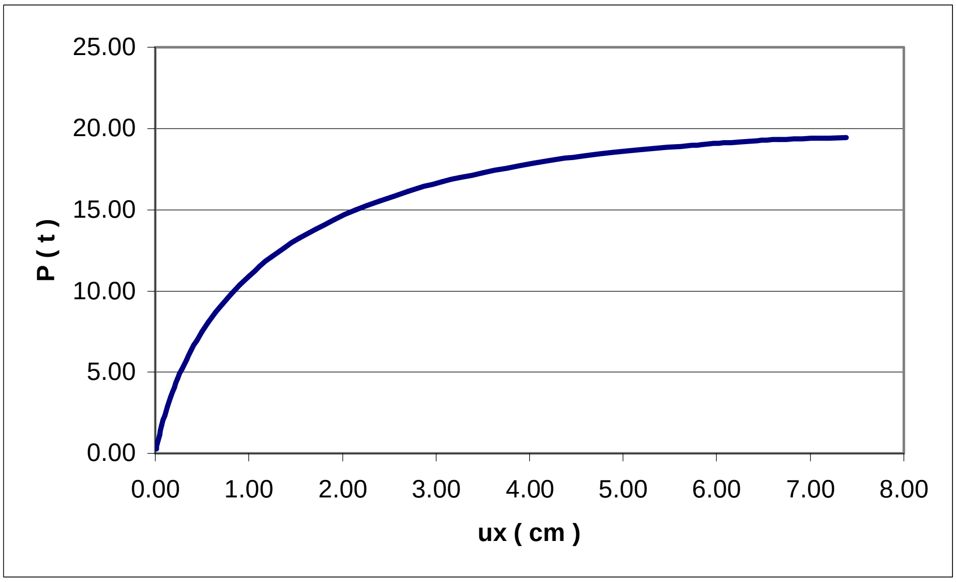

Fig. 4.49 Load-Displacement curve of axially loaded members without tie rods

The results obtained from finite element nonlinear analysis of flexurally loaded members without tie rods were shown in Figure 4.50. This Figure also showed the nominal flexural strength of tested members according to AISI and Eurocode3. While Figure 4.51 presents such comparison for members attached with tie rods. Column heights in these Figures represent the ratio (M/Mc). The load (M) is the flexural strength of the member according to nonlinear analysis, AISI, or Eurocode3. The load (Mc) is the Eigen analysis buckling load.

It could be observed from these Figures that there was accepted agreement between Eigen finite element analysis and nonlinear finite element analysis. Results of nonlinear analysis were very close to Eigen analysis in cases of smaller thickness. Deviation of nonlinear analysis from Eigen analysis increased as the thickness increased. Load-displacement curves of flexurally loaded members showed in Figure 4.52 for flexurally loaded members without tie rods. Displacement was measured at the junction between the web and bottom flange for mid-span cross-section.

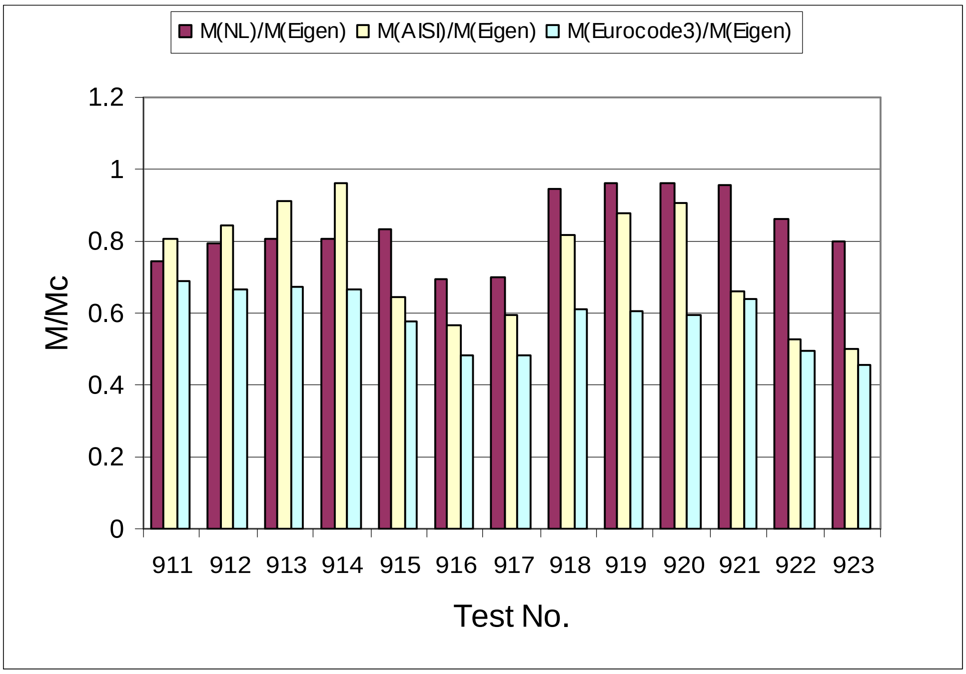

Fig. 4.50 Failure load of flexurally loaded members without tie rods

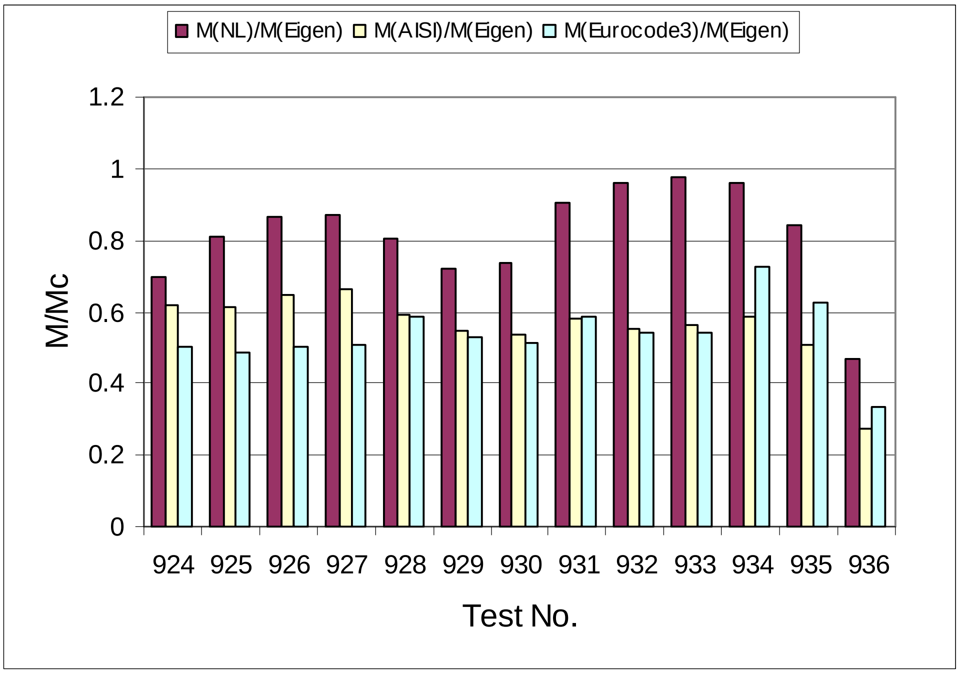

Fig. 4.51 Failure load of flexurally loaded members with tie rods

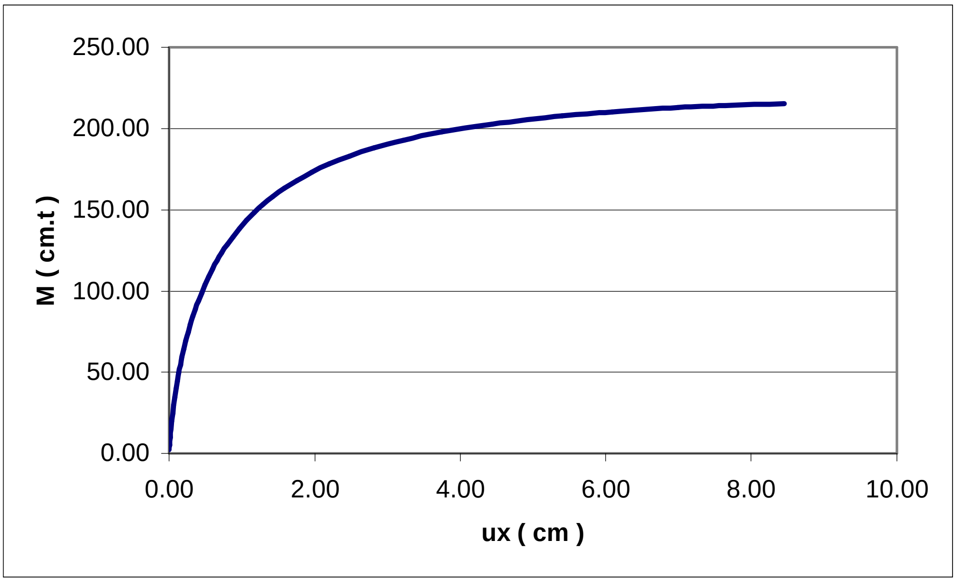

Fig. 4.52 Load-Displacement curve of flexurally loaded members without tie rods

4.8 Interaction of Axial load and flexural load

In this section 12 tests were investigated under axial and flexural loads simultaneously. Figures 4.53 to 4.64 show the interaction diagrams of these tests for finite element analysis, AISI, and Eurocode3. In these figures the X-axis represented the ratio (M/Mc). M is the flexural strength of the member undergoing axial loads and flexural loads according to finite element analysis, AISI, or Eurocode3. Mc is the flexural strength of the member according to finite element analysis when the member is only subjected to flexural loads. While the Y-axis represented the ratio (P/Pc). P is the axial strength of the member undergoing axial loads and flexural loads according to finite element analysis, AISI, or Eurocode3. Pc is the axial strength of the member according to finite element analysis when the member is only subjected to axial loads.

Figure 4.53 represented the interaction diagram of axially loaded members corresponds to test No. 115 against flexurally loaded members corresponds to test No. 531. This member had web depth of 300mm, flange width of 90 mm, and thickness of 2mm. This section may be considered a deep thin section.

Figure 4.54 represents the interaction diagram of axially loaded members corresponds to test No. 128 against flexurally loaded members corresponds to test No. 544. This member had web depth of 300mm, flange width of 90 mm, and thickness of 2mm. This section may be considered a deep thin section.

Figure 4.55 represents the interaction diagram of axially loaded members corresponds to test No. 245 against flexurally loaded members corresponds to test No. 661. This member had web depth of 300mm, flange width of 90 mm, and thickness of 2mm. This section may be considered a deep thin section.

Figure 4.56 represents the interaction diagram of axially loaded members corresponds to test No. 258 against flexurally loaded members corresponds to test No. 674. This member had web depth of 300mm, flange width of 90 mm, and thickness of 2mm. This section may be considered a deep thin section.

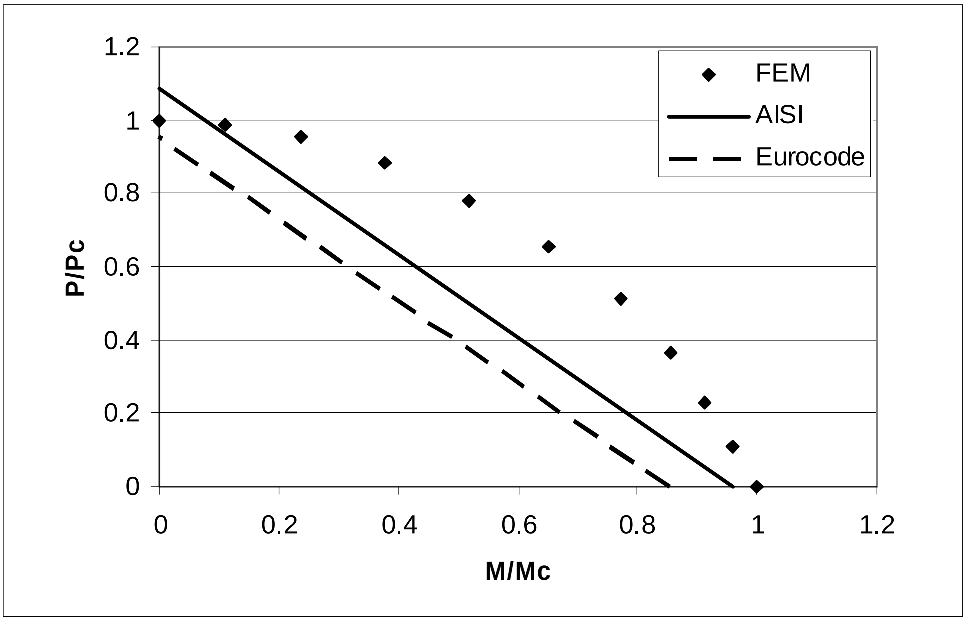

Fig. 4.53 Interaction diagram of axial test No. (115) against flexural test No. (531)

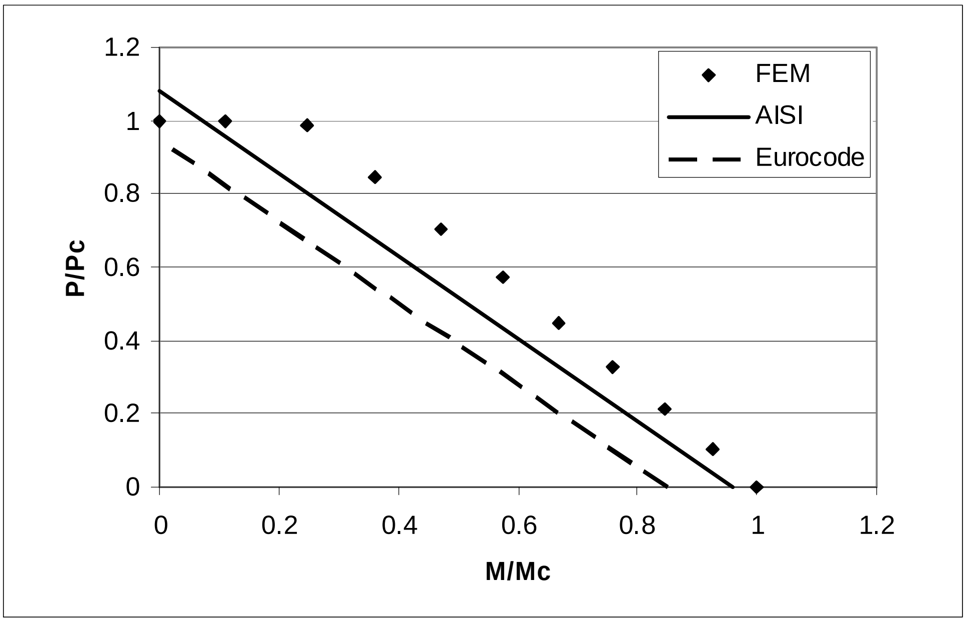

Fig. 4.54 Interaction diagram of axial test No. (128) against flexural test No. (544)

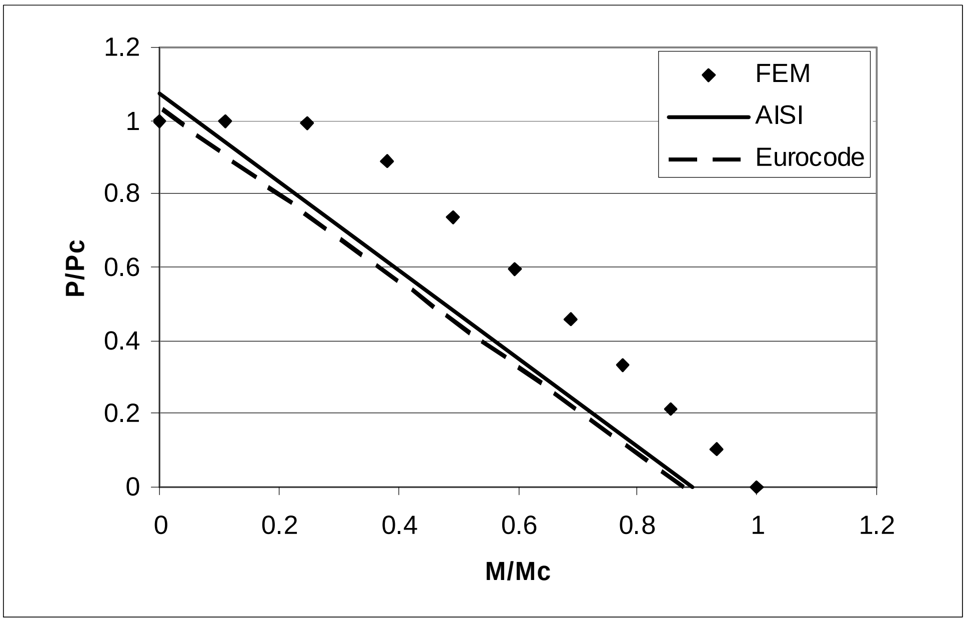

Fig. 4.55 Interaction diagram of axial test No. (245) against flexural test No. (661)

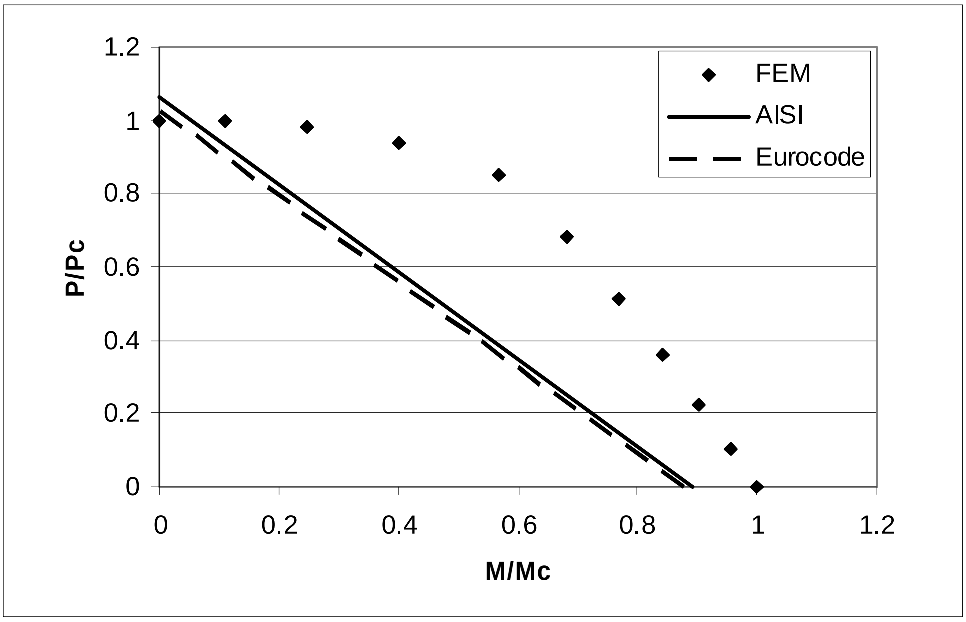

Fig. 4.56 Interaction diagram of axial test No. (258) against flexural test No. (674)

As shown in Figures 4.53, 4.54, 4.55, and 4.56, both of AISI and Eurocode3 represented the interaction as a straight line. Finite element represented the interaction as a curve. Lines of AISI and Eurocode3 were parallel, but they intersect with finite element interaction diagram at very high levels of axial forces. Eurocode3 is conservative with respect to finite element results. It is more conservative than AISI. The interaction diagram of AISI is generally conservative, but it is non-conservative for very low bending moments.

Figure 4.57 represented the interaction diagram of axially loaded members corresponds to test No. 219 against flexurally loaded members corresponds to test No. 635. This member had web depth of 300mm, flange width of 90 mm, and thickness of 2mm. This section may be considered a deep thin section.

Figure 4.58 represents the interaction diagram of axially loaded members corresponds to test No. 232 against flexurally loaded members corresponds to test No. 648. This member had web depth of 300mm, flange width of 90 mm, and thickness of 2mm. This section may be considered a deep thin section.

As shown in Figures 4.57 and 4.58, both of AISI and Eurocode3 represented the interaction as a straight line. Finite element represented the interaction as a curve with a very large radius of curvature, so that it seems to be a straight line. Lines of AISI and Eurocode3 were parallel. Eurocode3 is conservative with respect to finite element results. It is more conservative than AISI. AISI showed a good agreement with finite element interaction diagram at high bending moments with low axial forces. It slightly disagrees with finite element interaction diagram at high axial forces with low bending moments.

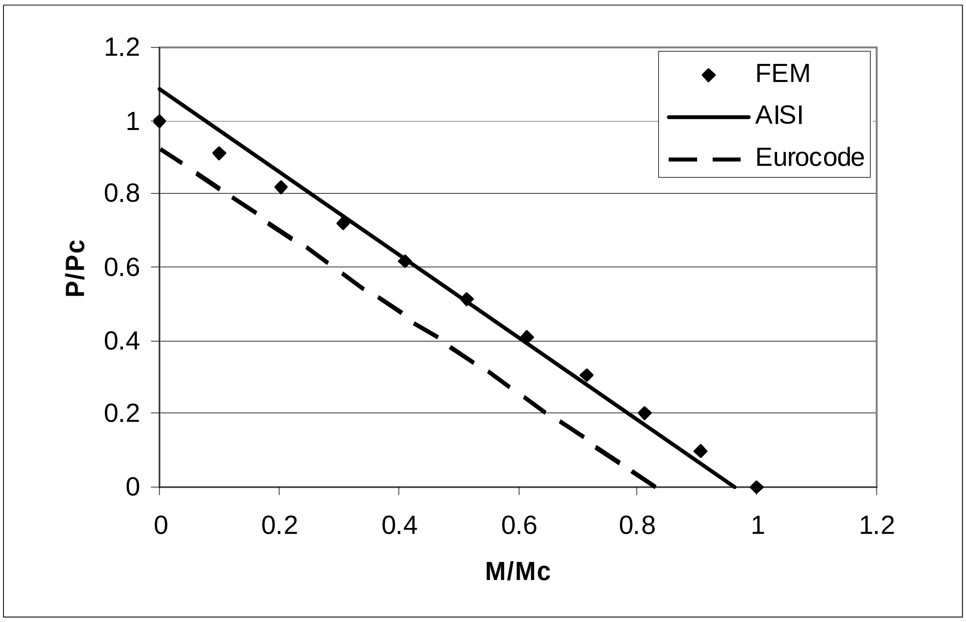

Fig. 4.57 Interaction diagram of axial test No. (219) against flexural test No. (635)

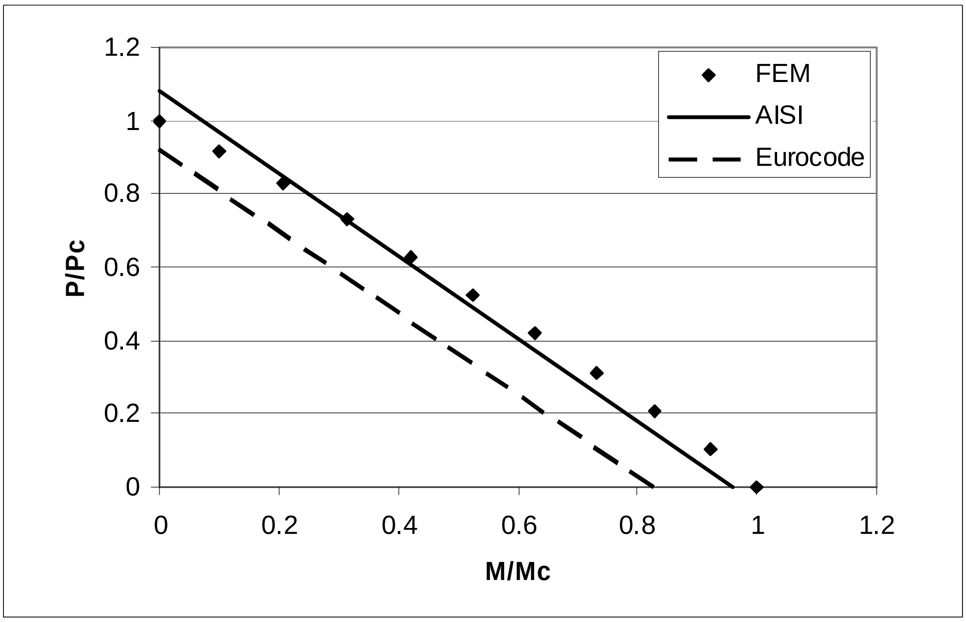

Fig. 4.58 Interaction diagram of axial test No. (232) against flexural test No. (648)

Figure 4.59 represented the interaction diagram of axially loaded members corresponds to test No. 226 against flexurally loaded members corresponds to test No. 642. This member had web depth of 200mm, flange width of 90 mm, and thickness of 2mm. This section may be considered a shallow thick section.

Figure 4.60 represents the interaction diagram of axially loaded members corresponds to test No. 235 against flexurally loaded members corresponds to test No. 651. This member had web depth of 200mm, flange width of 60 mm, and thickness of 1.5mm. This section may be considered a shallow thin section.

Figure 4.61 represents the interaction diagram of axially loaded members corresponds to test No. 248 against flexurally loaded members corresponds to test No. 664. This member had web depth of 200mm, flange width of 60 mm, and thickness of 1.5mm. This section may be considered a shallow thin section.

As shown in Figures 4.59, 4.60, and 4.61, both of AISI and Eurocode3 represented the interaction as a straight line. Finite element represented the interaction as a curve. Lines of AISI and Eurocode3 intersect with each other at high bending moment levels. AISI was generally conservative with respect to finite element interaction diagrams. It showed perfect agreement at zero axial force value. Eurocode3 interaction diagram was non-conservative compared with finite element results at very high levels of axial forces. Eurocode3 was more conservative for high moments. It even showed a good agreement with finite element interaction diagram at high bending moments.

Figure 4.62 represents the interaction diagram of axially loaded members corresponds to test No. 242 against flexurally loaded members corresponds to test No. 658. This member had web depth of 300mm, flange width of 60 mm, and thickness of 2mm. This section may be considered a deep thin section.

Figure 4.63 represents the interaction diagram of axially loaded members corresponds to test No. 255 against flexurally loaded members corresponds to test No. 671. This member had web depth of 300mm, flange width of 60 mm, and thickness of 2mm. This section may be considered a deep thin section.

As shown in Figures 4.62 and 4.63, both of AISI and Eurocode3 represented the interaction as a straight line. Finite element represented the interaction as a curve. Lines of AISI and Eurocode3 intersect with each other at intermediate bending moment levels. AISI showed perfect agreement with finite element interaction diagram at zero bending moment, while at was non-conservative at zero axial forces. AISI was generally conservative except for very high levels of bending moment. Eurocode3 was generally conservative with respect to finite element interaction diagram. It only was non-conservative at very high levels of axial forces or at very high levels of bending moments.

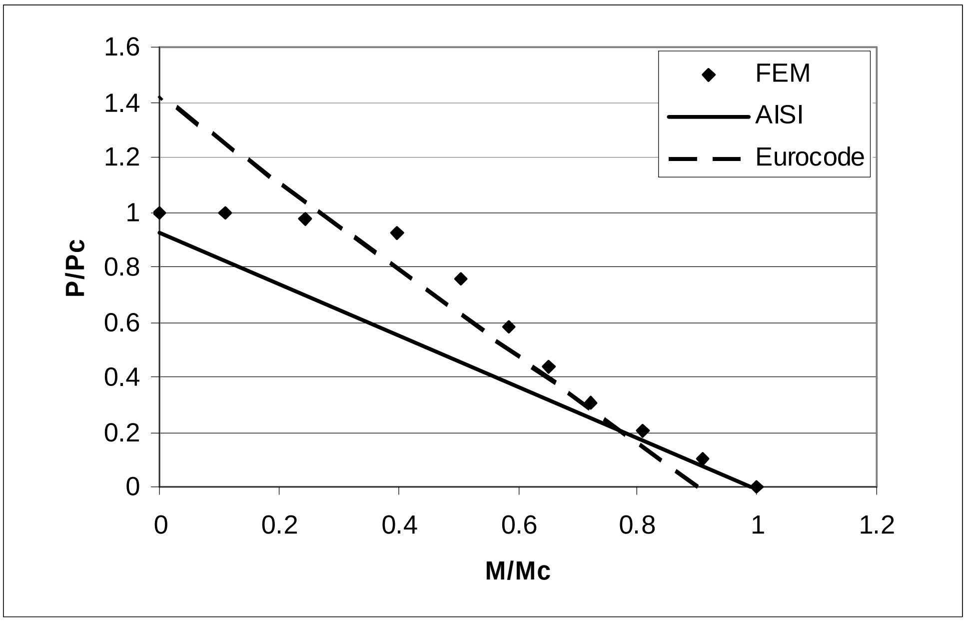

Fig. 4.59 Interaction diagram of axial test No. (226) against flexural test No. (642)

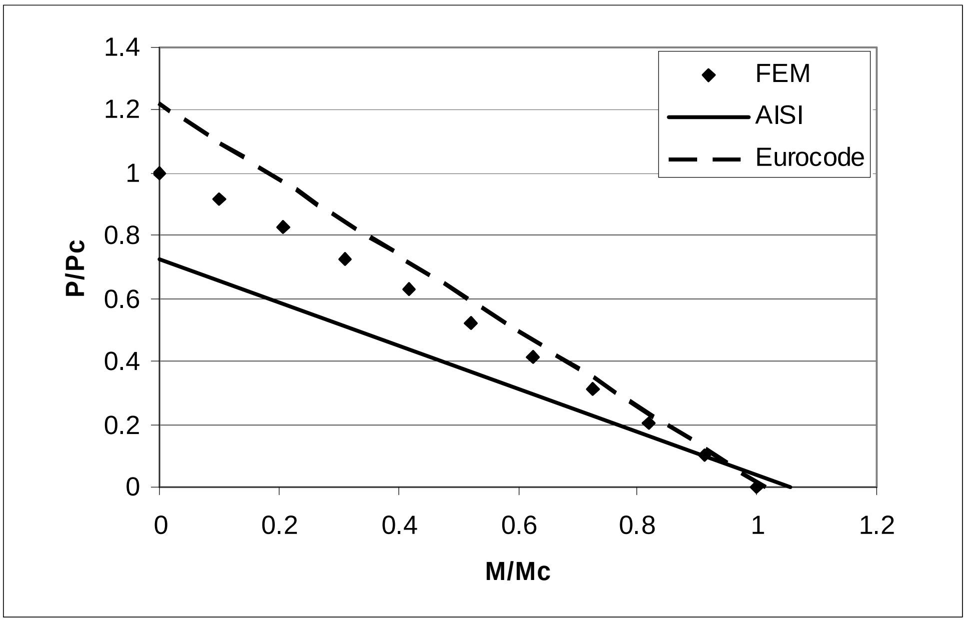

Fig. 4.60 Interaction diagram of axial test No. (235) against flexural test No. (651)

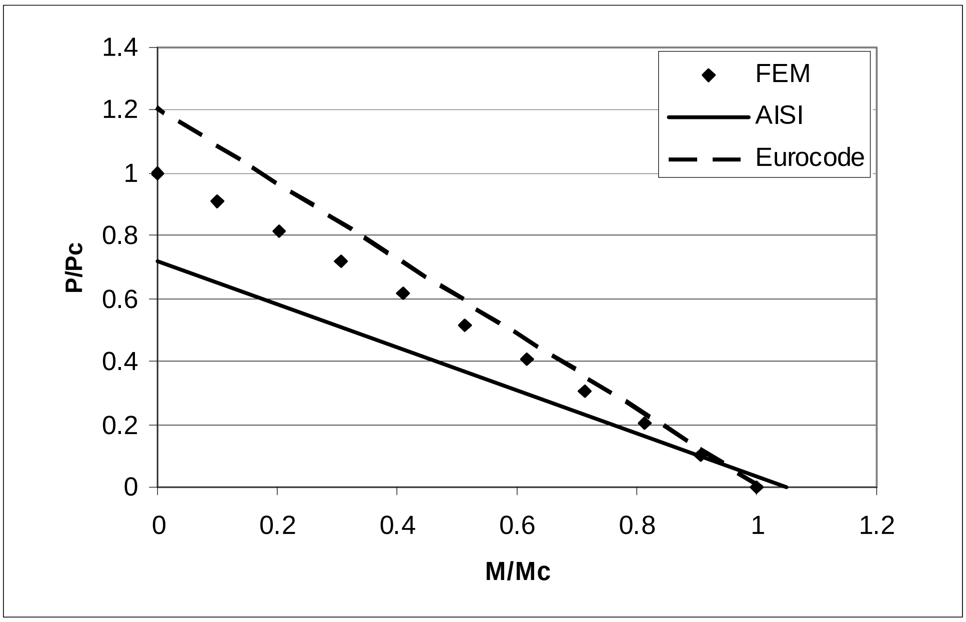

Fig. 4.61 Interaction diagram of axial test No. (248) against flexural test No. (664)

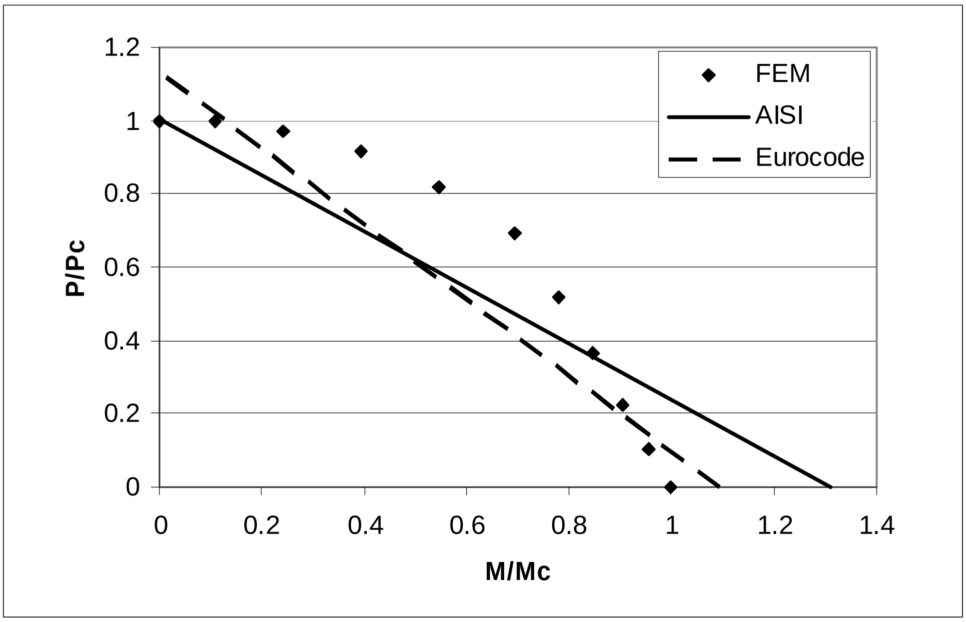

Fig. 4.62 Interaction diagram of axial test No. (242) against flexural test No. (658)

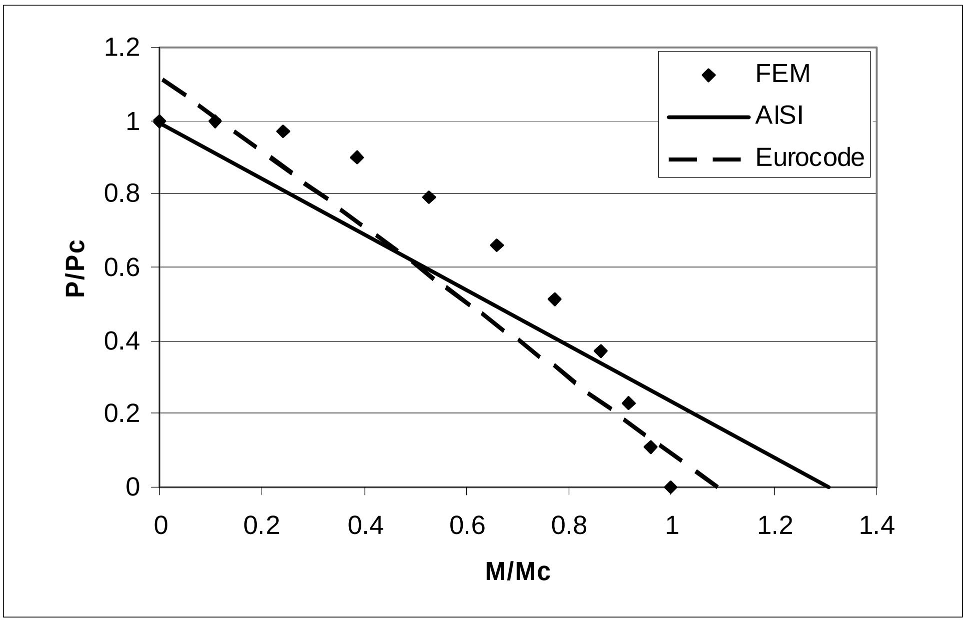

Fig. 4.63 Interaction diagram of axial test No. (255) against flexural test No. (671)

Figure 4.64 represented the interaction diagram of axially loaded members corresponds to test No. 151 against flexurally loaded members corresponds to test No. 567. This member had web depth of 300mm, flange width of 60 mm, and thickness of 2mm. This section may be considered a deep thin section. As shown in Figure, both of AISI and Eurocode3 represented the interaction as a straight line. Finite element represented the interaction as a curve with a very large radius of curvature, so that it seems to be a straight line. Lines of AISI and Eurocode3 intersect with each other. Both of AISI and Eurocode3 interaction diagrams were non-conservative compared with finite element results. AISI was more conservative for low moments. It even coincides with finite element interaction diagram at zero bending moment. Eurocode3 was generally non-conservative.

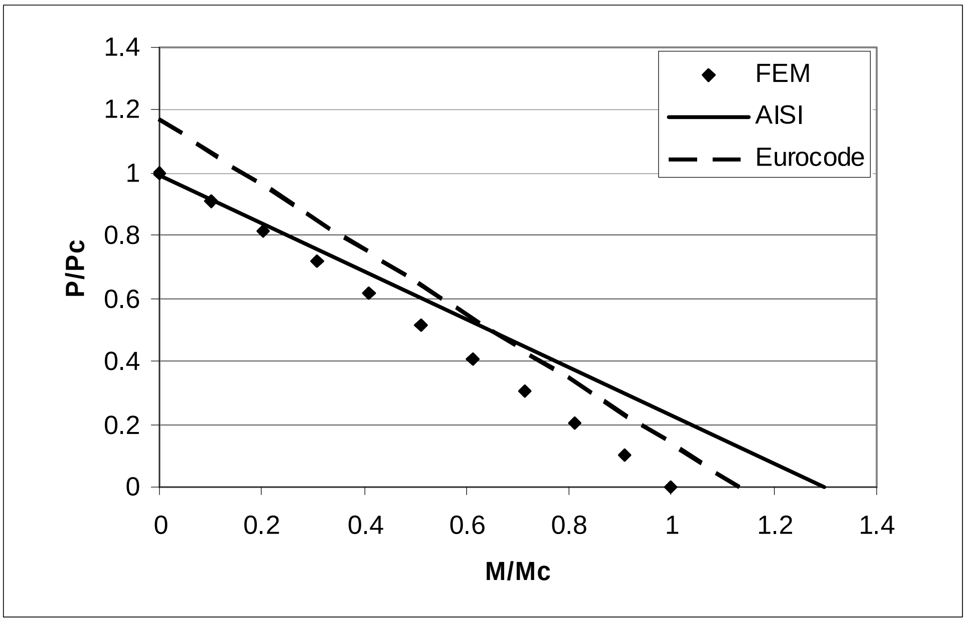

Fig. 4.64 Interaction diagram of axial test No. (151) against flexural test No. (567)