STATISTICAL EVALUATION OF ROTATION CAPACITY OF MOMENT CONNECTIONS

D. Beg, University of Ljubljana, Slovenia
E. Zupančič, University of Ljubljana, Slovenia

ABSTRACT

The paper describes the reasons that cause rotation capacity of moment connections strongly dependent on material properties of components of such connections. Then a statistical evaluation of the rotation capacity of typical moment connections with respect to the variation of the material properties of individual components was performed. The Monte Carlo method was used and 10,000 calculations were performed in each analysis. Log-normal distribution was assumed for yield strength f_y and ultimate strength f_u with the range of typical mean values and coefficients of variation from literature. The results show that considerable variation in rotation capacity is obtained in some cases.

INTRODUCTION

Besides strength and stiffness, rotation capacity is also very important characteristic of moment connections of steel structures. Until recently there have been no general methods for the determination of rotation capacity available, except tests and sophisticated FE analysis. Also EN 1993-1-8 (1), a very detailed standard on connections in steel structures, only briefly addresses this topic by giving some requirements to achieve sufficient ductility. For these reasons it is not surprising that several research groups are working on this problem (2, 3, 4, 5) and the authors of this paper together with I. Vayas have recently developed an analytical method that enables the assessment of rotation capacity of moment connections based on a component approach from EN 1993-1-8 (6, 7). From test results and extensive numerical simulations for each relevant component, deformation capacities and simplified bilinear force-displacement relations were established. By suitable mechanical model the components were assembled to model connection behaviour and to determine the rotation capacity.

Studying the problem and applying the developed method, it became evident that rotation capacity is very sensitive to the changes of basic material properties, yield stress f_y and tensile strength f_u, of individual components. It was observed that nominal values of f_y and f_u that are usually known at the design stage do not always give satisfactory results, as the real values are usually higher and most likely also some differences between individual components take place.

DESCRIPTION OF THE PROBLEM

The rotation capacity of the joint is governed by its weakest component. When the weakest component reaches its ultimate resistance, also the resistance of the joint is exhausted. This is exactly true for a component method, but also in reality (tests, FE simulations) there is very limited possibility for shedding of forces between different parts of the connection, and the resistance of the connection usually drops after the resistance of the critical part is reached. This means that the critical component contributes to the rotation capacity of the connection its full deformation capacity and other components contribute only deformations reached at the same loading level (see Figure 1).

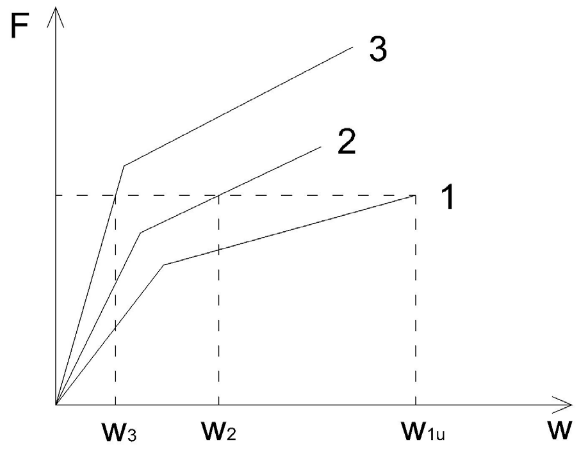

Figure 1. Contribution of components to the rotation capacity

One of the most important issues when determining the rotation capacity is the strength of components and especially relative difference in strength between components. This is demonstrated in Figure 2. For the sake of simplicity the connection is composed of only two components, represented by bilinear inelastic force-displacement diagrams, one in tension and one in compression (Figure 2a).

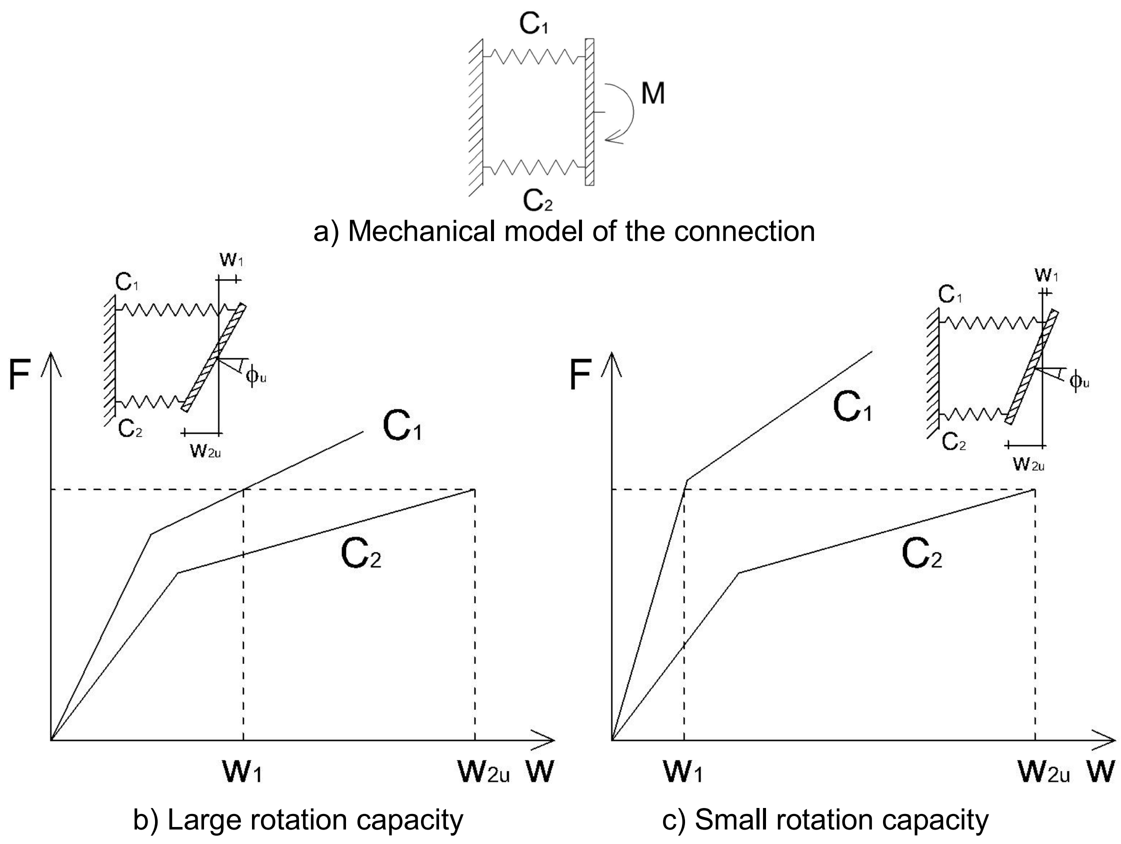

Figure 2. Influence of strength of components on the rotation capacity

In the first case the resistance of both components is similar, with component C_2 being decisive (Figure 2b). As component C_1 is in inelastic state when the resistance of C_2 is reached, its contribution to the rotation capacity is large. At slightly higher resistance of component C_1 (Figure 2c) its contribution to the rotation capacity decreases considerably, as this component remains in the inelastic state.

Such scenario can easily happen in reality. At the design stage only characteristic values of f_y and f_u are known and the rotation capacity is determined based on these values (case in Figure 2b). Real values of f_y and f_u are higher than the characteristic values, as characteristic values are more or less lower guaranteed values. For grade S235 the increase of strength goes up to 30% and for S355 the increase is somewhat smaller. The case in Figure 2c can be regarded as a situation, where the resistance of component C_1 was increased due to differences between characteristic and real material properties, while the resistance of component C_2 remained almost unchanged. The result is much smaller rotation capacity. In this case the actual behaviour is on the unsafe side compared to the design values.

Certainly, it is possible to find the opposite situation, where the real behaviour is on the safe side. The main conclusion is that the rotation capacity is very sensitive to the variability of material strength parameter. This is not a specific problem of a component method, but is immanent to the behaviour of joints when ductility is considered.

STATISTICAL PARAMETERS AND METHODS

Statistical analysis of typical moment connections was performed to assess how the variation of basic material properties f_y and f_u of individual components influences the rotation capacity of a connection. For basic random variables yield strength of column web, column flange, end-plate and tensile strength of bolts was selected. Log-normal distribution was applied to all random variables with the following four combinations of mean m_y and coefficient variation v_y:

- A – m_y = 1.18 f_y, v_y = 0.08
- B – m_y = 1.18 f_y, v_y = 0.10
- C – m_y = 1.12 f_y, v_y = 0.05
- D – m_y = 1.12 f_y, v_y = 0.08

where f_y is a nominal value from EN 1993-1-1.

Different authors (8, 9, 10) also propose log-normal distribution and case A as the most suitable for structural steel. Case B gives larger scatter and cases C and D smaller scatter of random variables than case A. For bolts of grade 8.8 in all calculations case C was taken into account to allow for more favourable statistical distribution of tensile strength in this case. In addition to the analysis with all four random variables, for case A also the Monte-Carlo simulation with only one active random variable at a time was performed. Other parameters were kept constant at their nominal (characteristic values).

DATA ON CONNECTIONS

Five different end-plate moment beam-to-column connections were analysed. They were designed for the purpose of statistical analysis, each with different decisive component with the smallest resistance. At the fifth connection all components have approximately equal resistance. The relevant data on connections are given in Table 1 and Figure 9.

Table 1. Data on connections 1 to 5

Connections	1	2	3	4	5
Column (S235)	HEAA 240	HEA 300	HEB 200	HEA 240	HEA 240
Beam (S235)	IPE 300	IPE 300	IPE 300	IPE 300	IPE 300
End plate (S235)	380/170/12	380/190/20	380/190/15	380/190/10	380/150/15
Bolts 8.8	M 16	M 20	M 20	M 16	M 16
w [mm]	110	110	110	110	90
x [mm]	60	60	60	60	60
e_1 [mm]	30	30	30	30	30
p_1 [mm]	80	80	80	80	80
p_2 [mm]	200	200	200	200	200
Critical component	CF	CWC	SWC	EP	CWC
CWC-Column web in compression, CF-Column flange in bending SWC-Column web panel in shear, EP- End plate in bending					

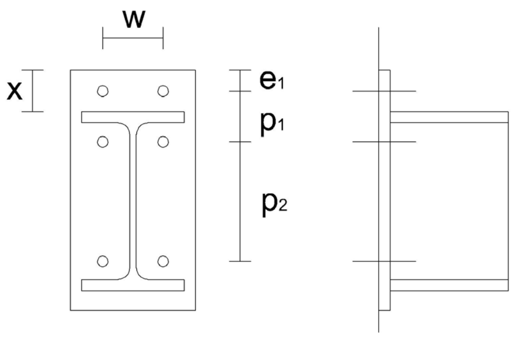

Figure 3. Geometry of connections

DETERMINISTIC ANALYSIS OF CONNECTIONS

For all five connections rotation capacity φ_u was determined at nominal values of material parameters with two methods: FE simulation (ABAQUS (11), solid finite elements) and own analytical method (6), where the resistance of components was determined in two ways – according to EN1993-1-8 and by replacing f_y with f_u when relevant (6) to get more accurate resistances. Comparison to numerical simulations (case c in Table 2) shows very good results when more realistic resistance of components is used – case b in Table 2 (very good agreement in three cases and conservative results in two cases), but some unsafe results when resistances from EN1993-1-8 were used (case a in Table 2).

Table 2. Results for rotation capacity

Connec-tion	a) Analytical – EC3		b) Analytical - f_u		c) Numerical simulations	
	Failure mode	φ_u $[rad]$	Failure mode	φ_u $[rad]$	Failure mode	φ_u $[rad]$
1	CF	0.055	CF	0.065	CF	0.115
2	CWC	0.133	CWC	0.081	CWC	0.087
3	SWC	0.148	CF	0.142	CWC	0.134
4	EP	0.045	EP	0.040	EP	0.103
5	CWC	0.175	CWC	0.104	EP	0.104

CWC-Column web in compression, CF-Column flange in bending
SWC-Column web panel in shear, EP-End plate in bending

Criteria for reaching ultimate rotation φ_u were stated by maximum equivalent plastic strains reached in different parts of connection: 0.1 for column web in tension, compression on shear and 0.2 for column flange and end-plate in bending.

RESULTS OF STATISTICAL ANALYSIS

Due to the limited number of pages of this paper it is not possible to present all the results obtained from the analysis. For connection 1 more results are given and for other connections only some results for case A of statistical parameters are presented (only for case a in Table 2).

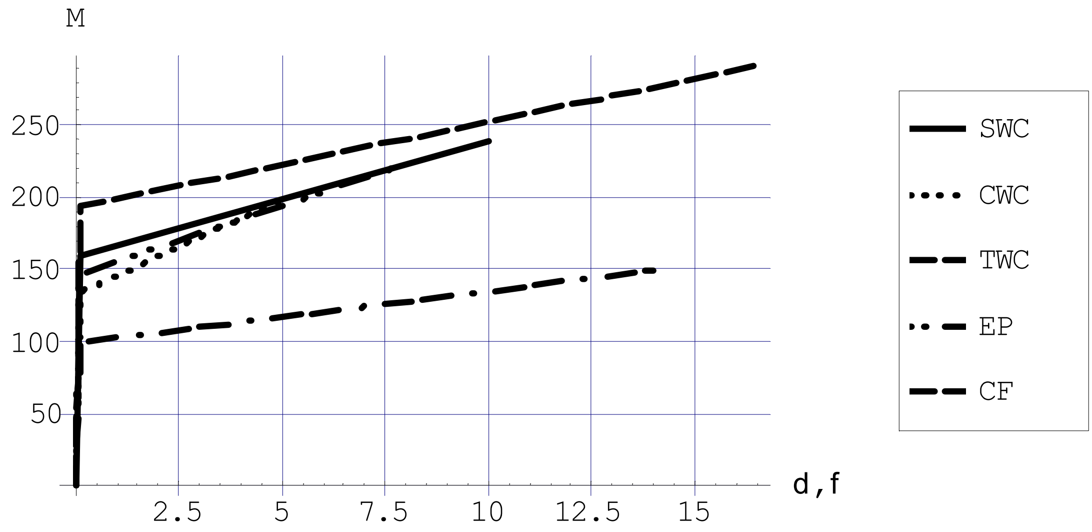

Figure 4. Connection 1: M-d diagram for components

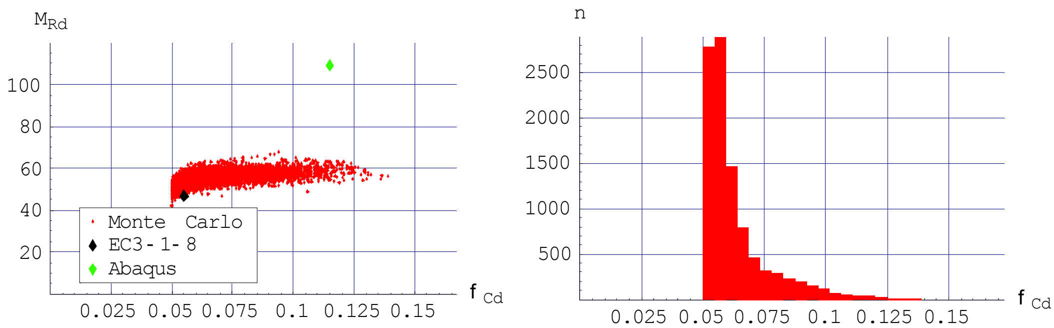

Figure 5. Connection 1: case A, all random variables active

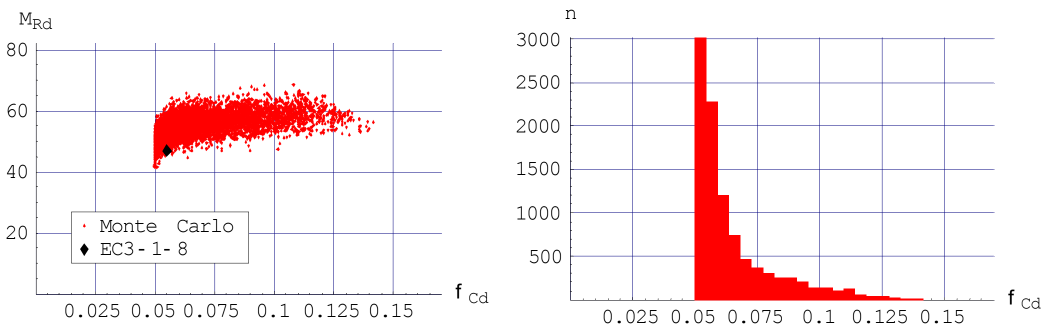

Figure 6. Connection 1: case B, all random variables active

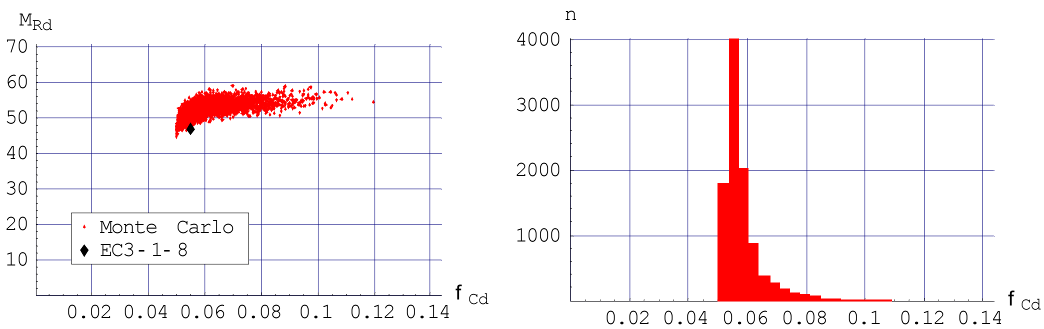

Figure 7. Connection 1: case C, all random variables active

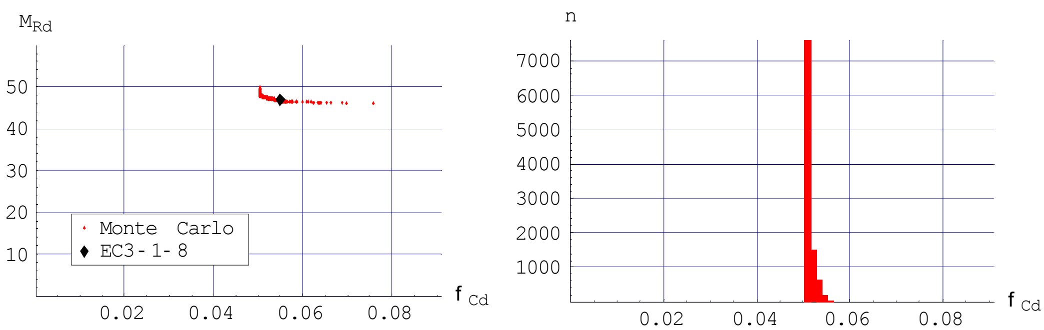

Figure 8. Connection 1: case A, only column web random variable

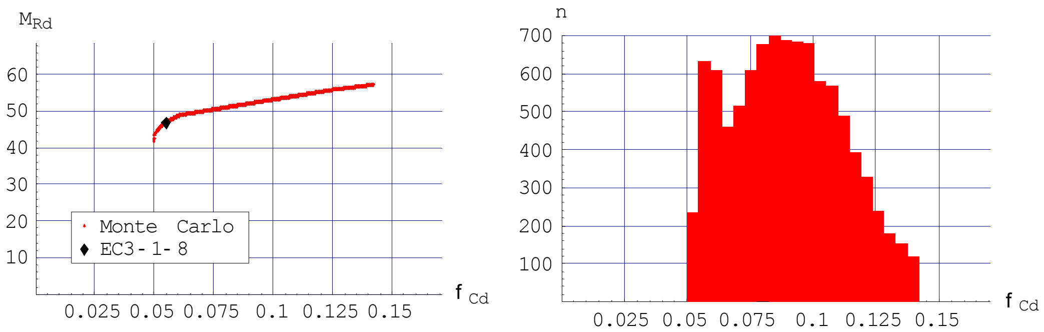

Figure 9. Connection 1: case A, only column flange random variable

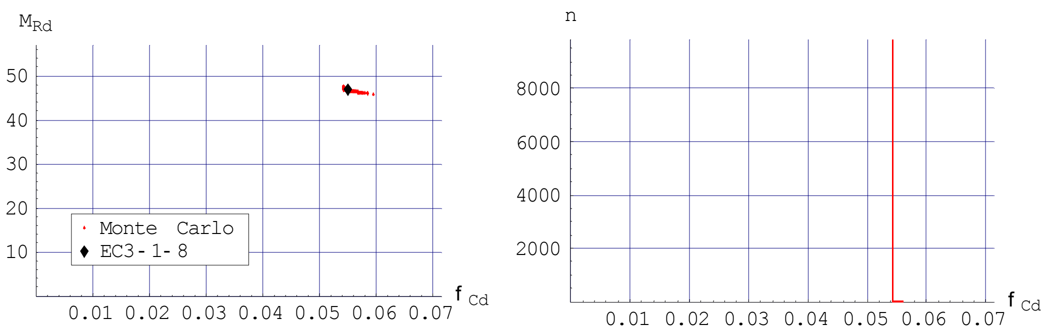

Figure 10. Connection 1: case A, only end-plate random variable

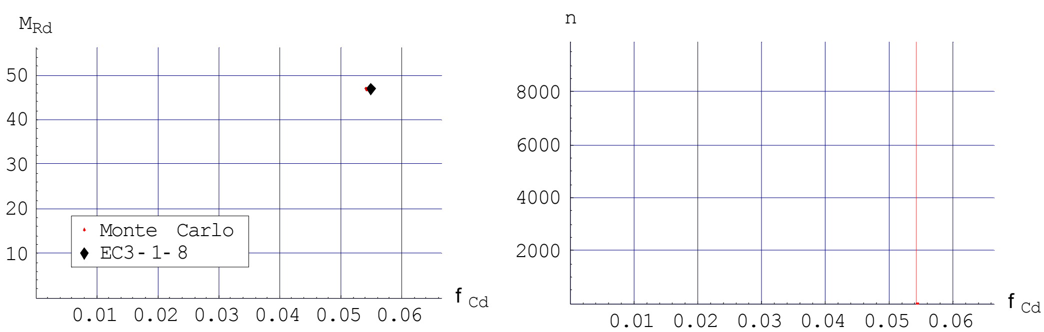

Figure 11. Connection 1: case A, only bolts random variable

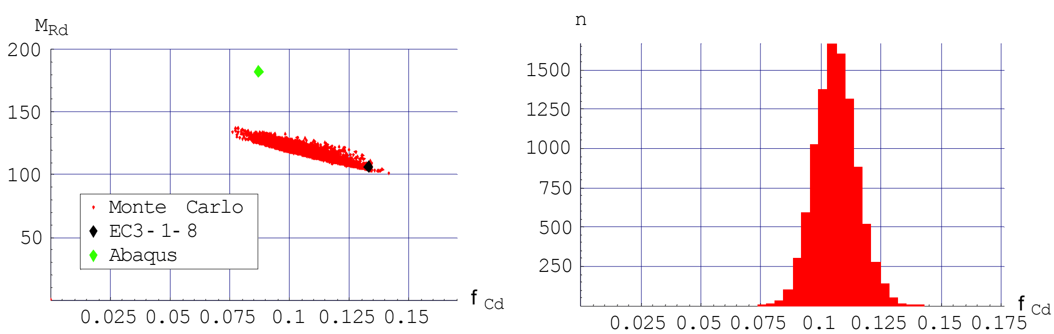

Figure 12. Connection 2: case A, all random variables active

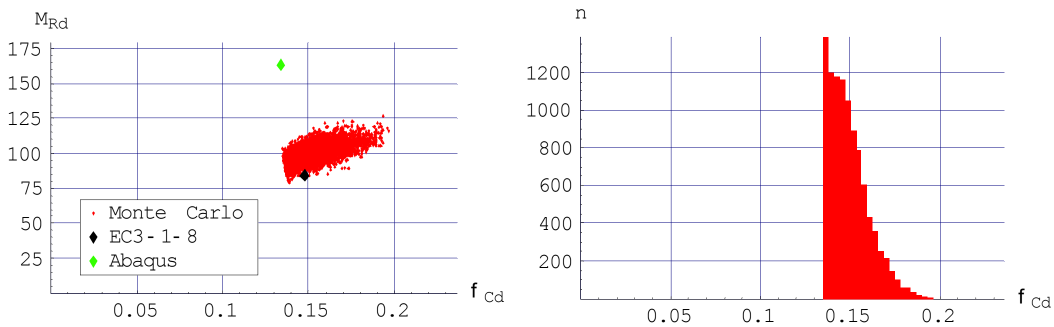

Figure 13. Connection 3: case A, all random variables active

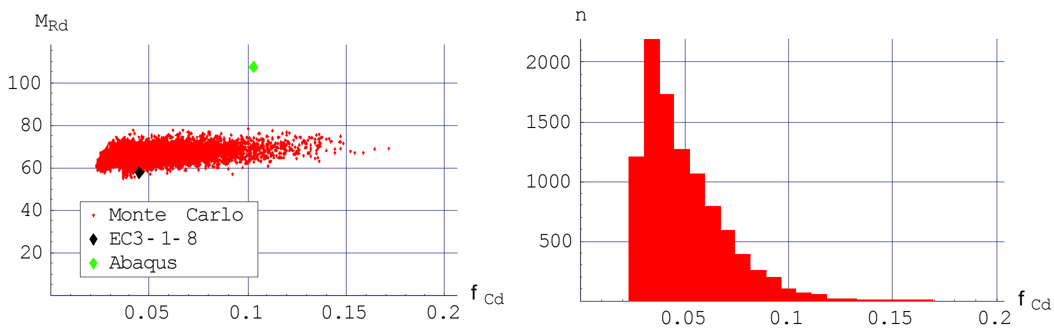

Figure 14. Connection 4: case A, all random variables active

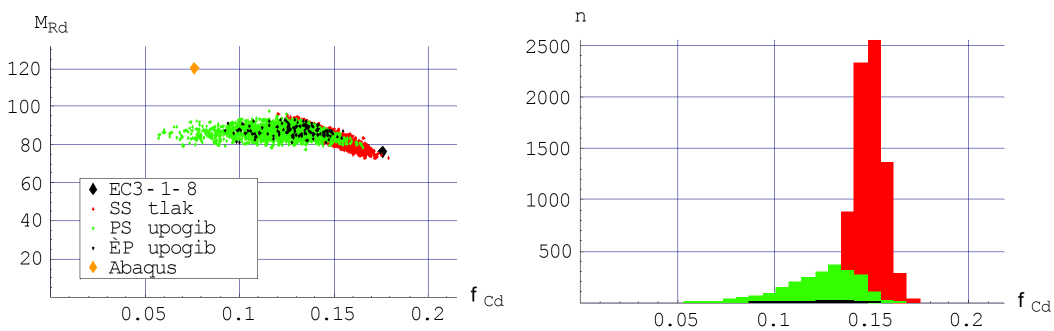

Figure 15. Connection 5: case A, all random variables active

Connection 1

From moment-displacement diagram (Figure 4) it is clear that column flange evidently has the lowest strength and should influence the rotation capacity to a large extent. In Figures 5 to 11 the calculated values of rotation capacity are plotted in diagrams M - ϕ (left) and the obtained distribution function of the rotation capacity is plotted at the right side. From these results the following observations can be made:

- The results for the ultimate capacity are in the range of 0.05 – 0.138 rad with the most probable result around 0.057 rad (0.055 rad at nominal values).

- Comparison of results for cases A, B and C shows that the results are very similar, but clearly reflect the statistical input parameters. Case B (Figure 6) gives the worst results and case C (Figure 7) gives the most favourable results.
- From Figures 9 – 11 it is evident that only the change of material properties of column flange strongly influences the rotation capacity, while other components have no influence. This is expected because their resistance is much larger than the resistance of column flange, and therefore they do not contribute significantly to the rotation capacity of the connection.

Connection 2 to 5

At connection 2 column web in compression is decisive, but the strength of other components is not much higher. The influence of the decisive component is not so pronounced as at connection 1. The most probable value of the rotation capacity is around 0.103.

At connection 3 column web in shear is decisive and the results are similar as at connection 1.

Also at connection 4 one component, end-plate, has evidently lower resistance and the influence of this component is large, while other components have little influence.

Connection 5 was designed such that all components have approximately equal resistance, only column web in tension is stronger. The scatter of results for the rotation capacity is very large (0.057 – 0.178) and qualitatively the results are similar as for connection 2 where also the resistance of its components does not differ much.

CONCLUSIONS

Rotation capacity of moment connections depends on the properties of several components and on the interaction of these components. Change in strength of one component can produce large change in the calculated rotation capacity. As at the design stage a designer does not know the real value of material properties of connections, but only nominal lower bound values, when fabricated, connections may have considerably different rotation capacity compared to the calculated value.

Obviously, statistical analysis can give more information about realistic behaviour in such conditions. For our own analytical method for the calculation of the rotation capacity we performed statistical evaluation, where material properties of individual components were random variables.

The following conclusions result from the statistical analysis:

- Scatter of results increases with more unfavourable statistical parameters.
- When one component has a considerably lower strength than other components, then only this component influences importantly the rotation capacity.
- When one component is evidently decisive, then the distribution function for the rotation capacity is asymmetric with a tail on the side of larger values and the most frequent value lies close to the lower bound.
- When more components have approximately equal strength, then the distribution function is asymmetric to the opposite side or almost symmetric and the most frequent value is closer to the upper bound.

- Values of rotation capacity, calculated on deterministic basis with nominal values (lower bound values) of material parameters, have a tendency to be close to the most frequent value. As the scatter of results is rather large this does not mean that the solution at nominal parameters is always a good estimate and on the safe side. Depending on the relations between components, the probability that the rotation capacity lies within ($\phi_{u\ NOMINAL} \pm 0.2\ \phi_{u\ NOMINAL}$) is assessed to 50% to 80% in the analysed cases.

These results show that the deterministic approach to the calculation of the rotation capacity based on nominal values of material properties may give unsatisfactory results. A possible solution could be statistical approach. Based on this approach reduction factors could be determined to be used in the simple deterministic calculation of the rotation capacity.

REFERENCES

(1) Eurocode 3: Design of steel structures, Part 1.8: Design of joints, prEN 1993-1-8: 2000.

(2) Coelho A., Bijlaard F., da Silva L. On the deformation capacity of beam-to-column bolted connection. Report AG-XXIII, ECCS-T10, April 2002, Ljubljana. 2002.

(3) Huber G., Tschemmernegg F. Modeling of beam-to-column joints. Journal of Constructional Steel Research, Vol. 45, 199-21. 1998.

(4) da Silva L. S., Coelho A. M. G. A ductility model for steel connections. Journal of Constructional Steel Research, Vol. 57, 45-70. 2001.

(5) Kuhlmann U., Sedlacek G., Kuhnemund F., Stangenberg H. Mitteilungen: Vorhandene rotationskapazitat wirtschaftlicher anschluskonstruktionen auf der basis des komponentenverhaltens fur die anwendung plastischer bemessungskonzepte im stahlbau. Institut fur konstruktion und entwurf stahl, holz- und verbundbau, Universitat Stuttgart, 2002.

(6) Beg D., Zupančič E., Vayas I. On the rotation capacity of moment connections. Journal of Constructional Steel Research, Vol. 60, 601-620. 2004.

(7) Zupančič E. PHD Thesis: Rotation capacity of steel connections. University in Ljubljani, Faculty for Civil and Geodetic engineering. Ljubljana, January 2004 (in Slovene lang.).

(8) Gulvanessian H., Holicky M., Markova J. Calibration of Eurocode reliability elements considering steel members. Eurosteel conference 2002, Coimbra Portugal, 1511-1520. 2002.

(9) Schleich J. B., Sedlacek G., Kraus O. Realistic safety approach for steel structures. Eurosteel conference 2002, Coimbra Portugal, 1521-1530. 2002.

(10) Fajkus M., Melcher J., Holicky M., Rozlivka L., Kala D. Design characteristics of structural steels based on statistical analysis of metallurgical products. Eurosteel conference 2002, Coimbra Portugal, 1541-1550. 2002.

(11) ABAQUS User's Manual, Version 5.8, 6.1, 6.2 & 6.3, Hibbitt, Karlsson and Sorensen Inc., USA, 2002.

Key words: Rotation capacity, Moment connections, Steel structures, Statistical analysis, Component method, Analytical method.