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Effect of varying component reliabilities on system reliabilities in flange-angle partially restrained steel moment connections

Trisha Chakravorty
Graduate Student, Dept. of Civil Engineering, IIT Kharagpur, Kharagpur, India

Aritra Chatterjee
Assistant Professor, Dept. of Civil Engineering, IIT Kharagpur, Kharagpur, India

Baidurya Bhattacharya
Professor, Dept. of Civil Engineering, IIT Kharagpur, Kharagpur, India

ABSTRACT: Component reliability based analysis and design typically does not quantify system reliability and redundancy. Steel moment connections, being critical components within buildings or bridges, are also structural systems in their own right, comprising bolt, weld, plate, beam and column components. In this work, a flange-angle partially restrained steel moment connection is analyzed using geometric and materially nonlinear finite element analyses to examine the effect of its component reliabilities on system reliability. Load sharing topology, system moment-carrying capacity and governing limit states are enumerated. Multiple stochastic simulations are performed at each design point to obtain system capacity distributions that are convolved with hazard curves to compute system reliabilities. From the data generated, a component to system reliability surface may be constructed that can potentially be used to optimize component design given a target system reliability and modify partial safety factors for use in design standards.

1. INTRODUCTION

Structural systems have non-zero failure probabili ties due to uncertainties associated with the basic variables which define their performance. Current load and resistance factor design (LRFD) satisfies acceptable failure probability limits for structural components that are chosen on the basis of engineering judgment and wide consensus on safe practices. However, lack of system level analysis may lead to over-designed or under-designed structures [Galambos (1990)], which is challenging to address within the current ambit of component reliability design procedures.

Load paths of moment-resisting frames involve steel moment connections comprising several components such as angles, plates, bolts and welds. Each component is designed on the basis of its individual limit state as per codal provisions. As with most other structural systems, there has not been adequate focus on system reliability of the connection as a whole, which represents the true measure of its performance. Connection systems are neither purely series nor parallel systems. Much of the mechanics still remain undiscovered, as does the comprehensive set of limit states that could potentially contribute to system failure.

This paper proposes a methodology to estimate system reliability of steel connections designed using component-based codal provisions. Specifically, we take up a flange-angle partially restrained connection configuration that connects a beam to a column with top and bottom seat angles bolted to beam flange and column flange. The load sharing network topology of the connection system is studied in the form of a fault tree including all possible modes of failure. Geometric and material nonlinear finite element analysis is performed on various combinations of diameters of beam-flange and column-flange bolts. Flexural demand is increased monotonically up to failure to obtain moment-rotation curves and governing limit states. System parameters (beam-flange and column-flange bolt diameters) are modified such that analysis captures the (random) most critical limit state for system failure initiation. Monte Carlo simulations are performed to obtain sets of moment-carrying capacities which are convolved with an assumed distribution curve to estimate system reliability. A three-dimensional system reliability surface may be plotted with the component reliabilities of beam-flange bolts and column-flange bolts and system reliability on three axes.

2. STEEL MOMENT CONNECTION AS A STRUCTURAL SYSTEM

A connection is a single structural component in the scale of a building, generally characterized by its force-deformation or moment-rotation curve [Deierlein et al. (1990)]. On a larger scale, the connection is a system in itself, comprising multiple structural elements. The steel connections most widely used are simple shear and moment connections. Connections are classified as rigid, semi-rigid or nominally pinned based on strength and rigidity by BS-EN-1993-1-8 (2005) and simple connections (transferring negligible moment) and moment connections (fully or partially restrained) by AISC (2016).

Structural steel connections transfer one or more of six force components. The demands on the connection system, obtained from a suitable global structural model in a design office, are distributed in its components using models that are usually linearly elastic incorporating the mechanics. The components are sized using an LRFD routine using the demands calculated at each limit state.

The load sharing network of a flange-angle partially restrained moment connection may be represented in the format of a fault tree. There are five major reliability elements—local failure of beam at beam-angle interface, failure of beam-angle interface, failure of angle, failure of angle-column interface and local failure of column at column-angle interface; these would be connected with an 'OR' gate, indicating that failure of even one leads to system failure.

Delving deeper into each major reliability element, there would be load paths ('OR' gate) and redundancies ('AND' gate). The first reliability block, local failure of beam at beam-angle interface, would comprise several events connected with an 'OR' gate, namely, beam net section failing in shear or flexure or shear-flexure interaction, beam flange failing in shear, beam web buckling, block shear failure and beam failing in bearing against bolts. The second reliability element, failure of beam-angle interface, comprises two events connected with an 'AND' gate: beam to angle friction contact failing and beam to angle bolt group failing. The latter further consists of three events connected with an 'OR' gate, namely, bolt group failing in bearing, in shearing and axially. The other three broad reliability elements may similiarly be expanded. Typically, only a single load path (which may or may not be dominant) is considered for design in spite of the presence of alternate load paths. For example, slip critical bolts are designed such that friction at the interface suffices without allowing the bolts to undergo bearing and shear at all. Apart from the load path used in design, the redundancy provided by alternate load paths usually remains unquantified.

3. STUDYING FLANGE-ANGLE PARTIALLY RESTRAINED STEEL MOMENT CONNECTION

3.1. *System definition*

In the connection configuration used in this work (Figure 1), top and bottom seat angles connect a wide-flange beam (supported member) to a column (supporting member). Single rows of two bolts (slip permitted) are used at each interface between an angle and a beam or column flange.

3.2. *Computation modelling*

Geometric and materially nonlinear finite element analysis is performed using Abaqus FEA Systems (2009). Beam and angles are modelled with eight noded solid finite elements with three degrees of freedom at each node and reduced integration

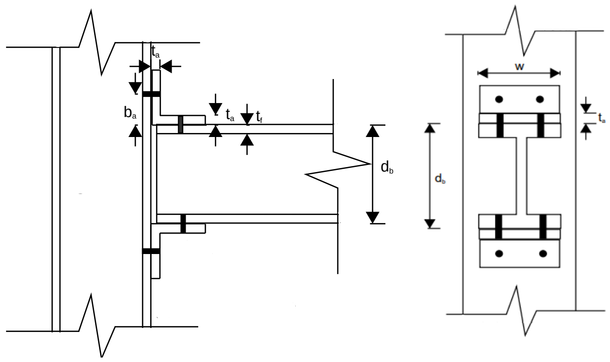

Figure 1: Side and front views of flange-angle bolted partially restrained connection configuration

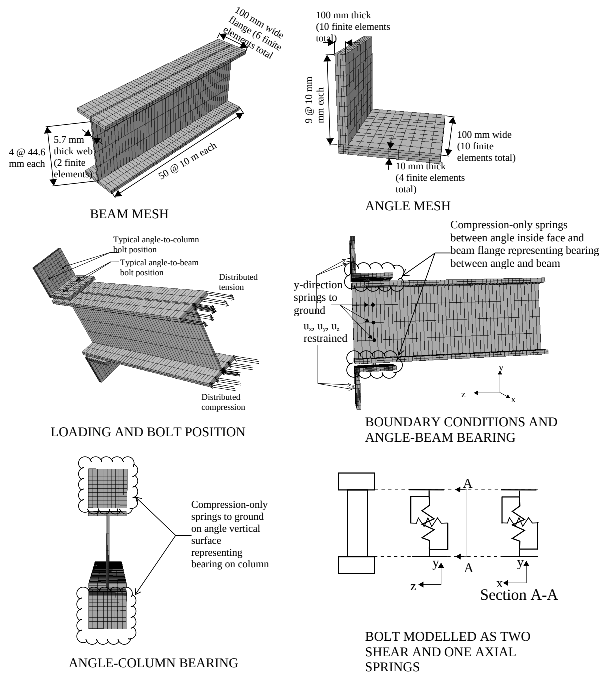

Figure 2: Computational modelling

(C3D8R in Abaqus). The scope of study is limited to beam, angles and bolts; the column is assumed to be perfectly rigid, and replaced with three translational restraints at each bolt attachment point. Bolts are idealized as spring elements. Bearing contact (ignoring friction) between interfaces is modelled with compression springs with arbitrarily high stiffness. Three gravity-direction springs to ground are attached to the beam web to simulate the effect of shear plate, but they are released in the beam axial direction so as not to provide major axis moment resistance. Mesh details, loading, boundary conditions and contact modelling is shown in Figure 2.

Yield and ultimate stresses for beam, angle and bolt material are taken to be 250 MPa and 410 MPa respectively. Stress-strain curves for beam and angle material (top row of Figure 3) is idealized as linear elastic up to yield stress, linear kinematic strain hardening up to ultimate stress and perfectly plastic beyond. Modulus of elasticity (E) and Poisson's ratio (ν) are assumed 210 GPa and 0.3 respectively. The bolt material is idealized as quadrilinear elastic including softening (middle and bottom rows of Figure 3). Axial yield ($f_{y,b}$) and ultimate ($f_{u,b}$) stresses are divided by a factor of $\sqrt{3}$ to obtain shear yield and ultimate stresses. Elastic strain at yield point is obtained by dividing yield stress by modulus of elasticity E for axial and shear modulus G for shear (where $G = \frac{E}{2(1+\nu)}$). Assumed relationships between the strain points is given in Eq. (1).

$$\varepsilon_e = f_{y,b}/E, \varepsilon_{p,1} = 100\varepsilon_e, \varepsilon_{p,2} = 1.5\varepsilon_{p,1}, \varepsilon_u = 2.5\varepsilon_{p,1} \tag{1}$$

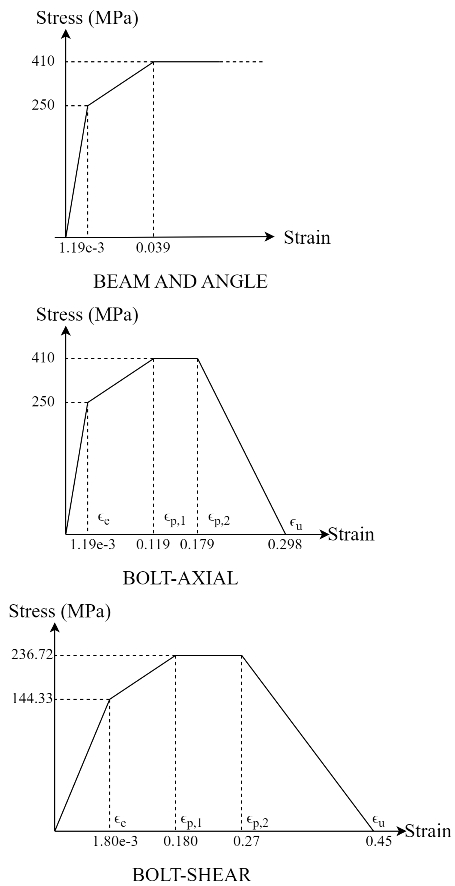

Figure 3: Stress strain curves

Each bolt is modelled as a set of three two-noded nonlinear springs, two shear and one axial, with load-deformation curves derived from shear and axial stress-strain curves and geometric properties of the bolt. Relationships between load (P) corresponding to stress (f) and deformation (δ) corresponding to strain (ε) are given in Eq. (2), where d is bolt diameter, t_f is thickness of beam flange and t_a is thickness of angle. Axial and shear load deformation curves are generated for various bolt diameters, that would be used later during parametric studies.

$$\begin{aligned} P &= f(\frac{\pi d^2}{4}) \\ \delta_{axial} &= \varepsilon_{axial}(t_f + t_a) \\ \delta_{shear} &= \varepsilon_{shear}(\frac{t_f + t_a}{2}) \end{aligned} \tag{2}$$

The loading pattern on the system is a major axis moment on the beam applied in the form of a tension-compression couple as line loads on top and bottom flanges. The load is monotonically increased quasi-statically to obtain the moment-rotation plot. Analysis continues up to ultimate moment-carrying capacity of the system, when the force-controlled simulation algorithm fails to converge at a specified minimum load increment.

3.3. Mechanics

The load sharing network topology includes five reliability elements in the load path. Failure at beam-angle interface and column-angle interface involves redundant load paths, through bolt group or direct interfacial friction; since slip is permitted in this analysis, the former is chosen for design. It is found that beam failure is not statistically significant in this configuration, so the corresponding reliability block is ignored, as is the fifth reliability element since the column is assumed to be sufficiently rigid and not been modelled.

Thus in the load path, four limit states remain (Figure 4), which is in agreement with considerations made during practice and identified by FEMA-356 (2000): (1) shear failure at beam flange to angle bolt group, (2) angle bearing or tensile rupture at bolted joint to beam, (3) angle flexural failure at bolted joint to column and (4) axial failure at angle to column bolt group. The limit states are symmetric about the beam axis under reversible load in elastic range.

From the finite element analysis, axial forces appear to develop in the beam-flange to angle bolts, which are generally assumed to only undergo shear. As Figure 5 shows, this gives rise to two additional limit states: (5) angle flexural failure at corner and (6) axial failure at beam-flange bolt group. Due to this axial force which counteracts the angle flexural demand at column bolt joint, the axial capacity for angle to column bolt group predicted by FEMA is found to be unconservative, while the angle flexure capacity is found conservative. In this work, bolt shear and axial responses have been modelled as independent springs, hence axial-shear interaction failure has not been captured. The statistically significant limit states and corresponding deformed configurations at failure are shown in Figure 6.

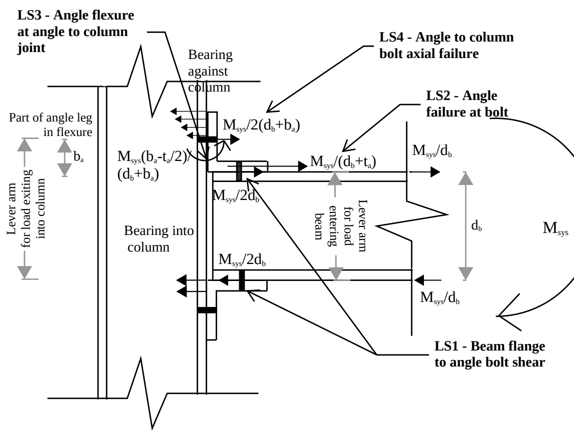

Figure 4: Load transfer mechanism and limit state demands as per FEMA-356 (2000)

3.4. Moment-rotation plot

The baseline design for the studied connection configuration is an Indian Standard ISMB 200 beam [IS-800 (2007)] with overall depth 200 mm, width 100 mm, flange thickness 10.8 mm and wed thickness 5.7 mm. Top and bottom seat angles are Indian Standard ISA100100 (dimensions 100 mm x 100 mm x 10 mm). Beam-flange and column-flange bolts have diameters 8 mm and 7mm respectively.

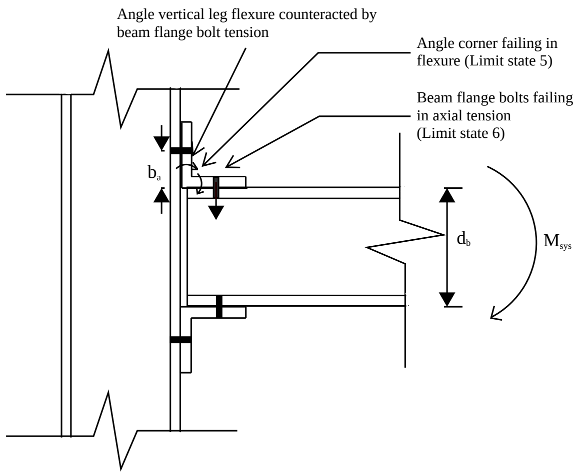

Figure 5: Additional limit states predicted by analysis

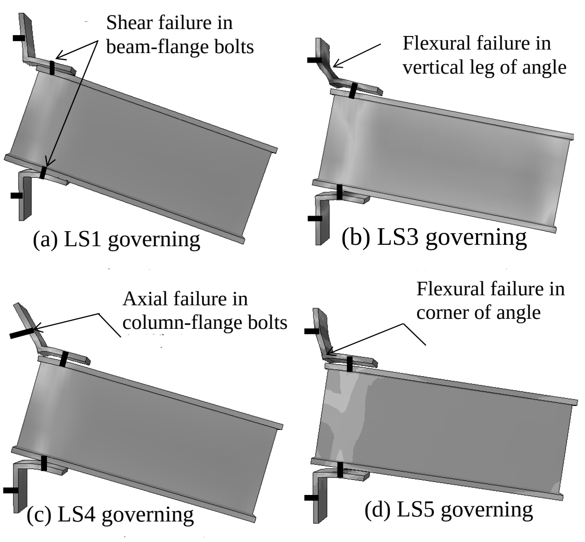

Figure 6: Deformed configurations of system when different limit states govern

Defining rotation as relative displacement between topmost and bottommost points of the beam divided by its overall depth, the moment-rotation curve of the configuration is obtained from finite element analysis (Figure 7). Failure is governed by the four bolts between beam flange and angle failing in shear at a moment of 7.39 kN-m. The system exhibits ductile response with rotation at failure, 0.045 radians, greater than ten times the rotation at first yield.

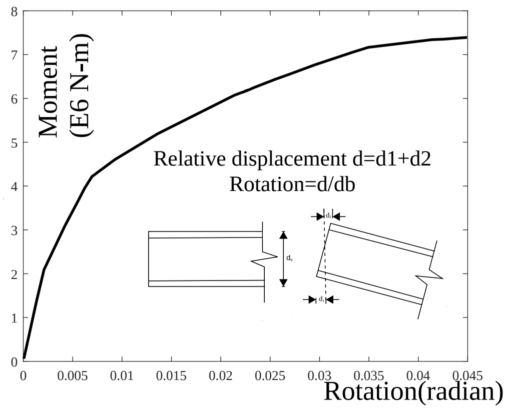

Figure 7: Moment-rotation curve for baseline design

3.5. Maximum acceptable demand for given design and as-designed component reliabilities

Maximum acceptable demand for the connection that has already been designed is determined. From IS-800 (2007), unfactored component demand of each of the four limit states is computed; the corresponding partial safety factors are applied. Next each of the four factored component capacities are mapped to a corresponding system capacity using the mechanistic model of FEMA-356 (2000). The factored design system capacity is a function of the four quantities; here, the minimum of the four. At design point, design system demand equals design system capacity. Dividing the design system demand by load factor and bias factor gives the mean system demand. Following this methodology, with load factor of 1.5 and bias factor 1.0, the mean system demand, or the just-acceptable system demand is 2.54 kN-m.

Once the system demand has been fixed, reliabilities of each component as designed can be calculated as $\beta_i = \frac{log_n \frac{\mu_{C_i}}{\mu_{D_i}}}{\sqrt{V_{C_i}^2+V_{D_i}^2}}$. Component demands are obtained from mechanics [FEMA-356 (2000)] from the mean system demand $\mu_{D_{sys}} = 2.54$ kN-m. Assumed coefficient of variation of each component is the same as the system, $V_{D_i} = 21\%$ and coefficients of variation of the capacity accounting for material and fabrication factors are assumed 10% and 5% respectively [Lin et al. (1988)], resulting in $V_{C_i} = 11.8\%$.

The component reliabilities obtained thus are

β_1=2.64, β_2=12.73, β_3=1.32 and β_4=4.32 from LS1 to LS4 [Figure 6]. According to the mechanics of FEMA-356 (2000) and component capacities of IS-800 (2007), LS3 (angle flexure) appears to be the critical element with lowest component reliability. The finite element analysis, however, shows LS1 (shear in beam-flange bolts) to be governing failure. This could be attributed to reduction in flexural demand in angle due to axial force in beam-flange bolts (Figure 5). In this work, LS1 is taken to be the critical element.

3.6. System reliability computation

Monte Carlo simulations with random yield and ultimate stresses of beam, angles and bolts and diameters of bolt are run up to failure to obtain the system capacity distribution. Mean value for all random quantities are taken as their nominal values. For a material, yield and ultimate stresses are considered fully correlated with coefficient of variation 10%. Angle and beam material are assumed fully correlated, while bolt material is modelled independently from it. Both material properties and diameters of eight bolts have a high mutual correlation of 80%. Coefficient of variation of bolt diameter is taken as 5%.

500 geometric and materially nonlinear random analyses are run to obtain the histogram of ultimate moment carrying capacities (Figure 8), which is found to have mean 6.93 kN-m and coefficient of variation 12%. The demand distribution is taken to be lognormal with the 'just acceptable' mean demand of 2.54 kN-m and coefficient of variation 21%.

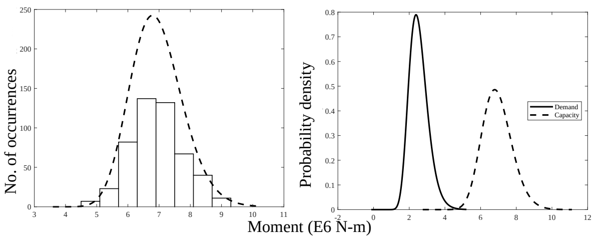

Figure 8: System demand and capacity distributions

With the demand and capacity distributions known, probability of failure of the system is computed using the convolution method.

$$P_{f_{sys}} = \int_0^\infty F_{C_{sys}}(m) f_{D_{sys}}(m) dm \qquad (3)$$

where F denotes the cumulative distribution function and f the probability density function. Failure probability is obtained using step size $dm = 0.01$ in the numerical integration of Eq. (3) and further, the reliability index is calculated as $\beta_{sys} = \Phi^{-1}(1 - P_{f_{sys}})$ where Φ is the standard normal cumulative distribution function.

In the baseline model, system reliability index is found to be 4.21, which is greater than the critical component reliability of 2.64. This indicates a beneficial system effect. In all the 500 runs, the beam-flange bolts failing in shear governed system failure. Unlike the deterministic system model where all four beam-flange bolts failed simultaneously, modelling randomness implies that the weakest bolt fails first. As a result, a minor axis moment develops and causes global instability; the full capacity of all the four beam-flange bolts may not be mobilized. This effect could have been avoided by using multiple rows of bolts.

3.7. Parametric studies

Parametric studies are carried out by varying beam-flange and column-flange bolt diameters. Governing limit states and deterministic moment-carrying capacities of each case are shown in Table 1 and Table 2 respectively. Moment-rotation curves for each combination is shown in Figure 9. Increasing diameter of the bolts governing failure (i.e., strengthening them) leads to increase in system capacity till the critical element changes. For example, when diameter of beam-flange bolts is increased from 8 mm to 10 mm keeping other parameters in the baseline model constant, the 7 mm column-flange bolts become the critical ones, and system capacity increases from 7.39 kN-m to 8.4 kN-m. Strengthening non-critical elements does not increase capacity but does affect ductility, which is seen to decrease due to added stiffness provided against rotation by a stronger non-critical element.

For each combination, 500 random simulations are run to obtain mean system capacity and coefficient of variation (Table 3). For some combina-

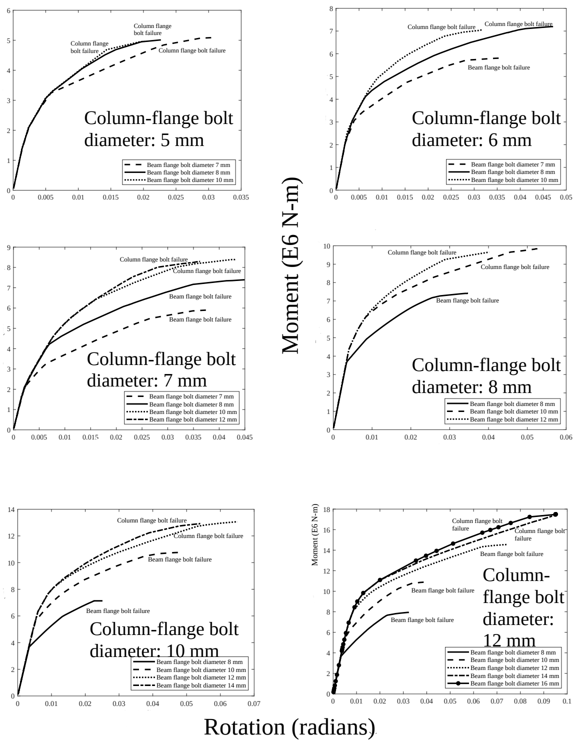

Figure 9: Moment-rotation curves for combinations of beam-flange and column-flange bolt diameters

tions, mixed-mode failure is observed, i.e., the existence of more than one statistically significant limit state. For example, for 10 mm beam-flange and 8 mm column-flange bolt diameters, in the deterministic run, the latter was the critical limit state, while three failure modes are found in the simulations: column-flange bolts (67%), beam-flange bolts (18%) and both simultaneously (15%).

3.8. Design application

A component to system reliability surface may be plotted with the data obtained above, using which the system may be designed based on target system reliability considerations, i.e., a target reliability may be set, and the required component reliabilities of the significant limit states decided from the surface.

4. CONCLUSIONS

Load paths of moment-resisting frames involve steel moment connections comprising several components such as angles, plates, bolts and welds. Connections are designed on a component-wise basis; there has not been adequate focus on system

Table 1: Governing limit states for combinations of beam-flange and column-flange bolt diameters (mm) (B: beam-flange bolts, C: column-flange bolts)

Column flange / Beam flange	5 mm	6 mm	7 mm	8 mm	10 mm	12 mm
7 mm	C	B	B	-	-	-
8 mm	C	C	B	B	B	B
10 mm	C	C	C	C	B	B
12 mm	-	-	C	C	C	B
14 mm	-	-	-	-	C	C
16 mm	-	-	-	-	-	C

Table 2: Deterministic system capacity (kN-m) for combinations of beam-flange and column-flange bolt diameters (mm) (B: beam-flange bolts, C: column-flange bolts)

Column flange / Beam flange	5 mm	6 mm	7 mm	8 mm	10 mm	12 mm
7 mm	5.0	5.8	5.9	-	-	-
8 mm	5.0	7.2	7.4	7.4	7.1	7.9
10 mm	5.0	7.0	8.4	9.8	10.8	10.9
12 mm	-	-	8.3	9.6	13.0	14.6
14 mm	-	-	-	-	12.9	17.4
16 mm	-	-	-	-	-	17.5

reliability of the connection as a whole, which represents the true measure of its performance.

A flange-angle partially restrained steel moment connection is taken up and load sharing topology, system moment-carrying capacity and governing limit states are studied. The aim of this work was to estimate system reliability of discrete design points of the connection corresponding to varying element reliabilities using Monte Carlo simulations on a geometric and materially nonlinear finite element model. The component to system reliability surface to be developed based on the results may be used to

Table 3: Results of random simulations of combinations of beam-flange and column-flange bolt diameters (mm) (B: beam-flange bolts, C: column-flange bolts, M: mixed, majorly column-flange bolts)

Beam flange bolt mean dia (mm)	Column flange bolt mean dia (mm)	Critical element	Mean capacity (kN-m)	CoV (%)	System reliability index
7	5	M	5.0	13.0	2.86
8	5	C	5.0	13.5	2.76
10	5	C	5.0	13.2	2.80
7	6	B	5.4	13.0	3.20
8	6	M	6.7	12.0	4.13
10	6	C	6.9	11.8	4.19
7	7	B	5.5	12.6	3.23
8	7	B	6.9	12.0	4.20
10	7	C	8.5	8.6	5.48
12	7	C	8.3	9.6	5.18
8	8	B	6.9	12.0	4.20
10	8	M	9.7	9.4	6.01
12	8	C	9.7	9.1	6.08
8	10	B	7.1	11.7	4.34
10	10	B	10.0	11.6	5.86
12	10	M	12.9	9.9	7.17
14	10	C	12.9	11.4	6.97
8	12	B	7.3	11.2	4.56
10	12	B	10.1	10.9	5.74
12	12	B	13.3	9.8	7.28
14	12	M	15.9	7.3	8.04
16	12	M	17.3	10.6	8.04

fix design component reliabilities given a set target reliability with the help of a gradient optimization routine or a system reliability sensitivity algorithm. Modified sets of resistance factors may be calculated from the component reliability requirements for typical connection systems or on a case-to-case basis in design offices. Further, this methodology may be applied to the finite number of steel connection topologies used in practice, and could someday be incorporated into design standards.

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