Risk Assessment in Engineering

Principles, System Representation & Risk Criteria

Annex

Example – Assessment of Structural Robustness

JCSS

Joint Committee on Structural Safety

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1 Description of the Example Structure – a High Rise Building

1.1 Loads, Material Properties and Structural Member Dimensions

A 40-storeyed steel building designed using a framed tube structural system is considered for analysis. The elevation of the building structural frame is shown in Figure 1. The overall dimensions of the building on plan are 24 m by 24 m and the height of each storey is 4 m.

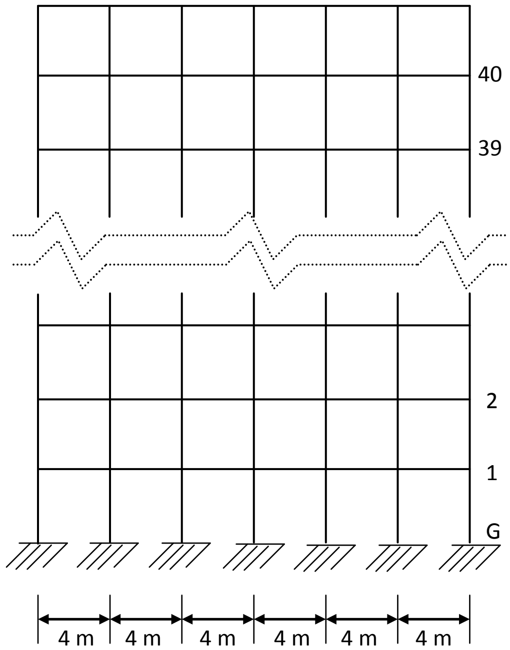

Figure 1. Elevation of the building frame.

The dead loads, live/imposed loads and wind loads are modelled as uncertain variables using the modelling approach and data in the JCSS Probabilistic Model Code (JCSS, 2001) and are given in Table 1. A load combination comprising self weight, long term live load, short term live load and wind load is considered for design.

Variable	Distribution	Mean	Coefficient of Variation
Density of steel	Normal	77 kN/m^3	0.01
Long term live load (sustained)	Gamma	0.5 kN/m^2	1.15
Short term live load (1 day)	Exponential	0.2 kN/m^2	1.60
Mass density of air	Deterministic	0.125 kg/m^3	–
Aerodynamic shape factor	Normal	1.10	0.12
Gust factor	Normal	2.65	0.12
Roughness factor	Normal	1.80	0.15
Reference wind speed (8 hours)	Weibull	5 m/s	0.60
Reference wind speed (1 year)	Gumbel	30 m/s	0.10
Model factor for wind pressure	Normal	0.80	0.20
Model factor for resistance	Normal	1.00	0.05
Model factor for load effect	Normal	1.00	0.10
Yield stress of steel	Lognormal	250 N/mm^2	0.07
Ultimate tensile strength of steel	Lognormal	400 N/mm^2	0.04
Modulus of elasticity of steel	Lognormal	200000 N/mm^2	0.03

Table 1. Modelling parameters for the load and resistance variables.

An additional consideration of design for "unidentified accidental loads" as provided for in Eurocode 1 (Actions on Structures) Part 1-7 (General Actions – Accidental Actions) (BS EN 1991-1-1:2006) is also made. For such "accidental" design situations, one of the specifications in Eurocode 1 Part 1-7 is to design "key elements" for a recommended lateral uniformly distributed load of 34 kN/m^2. For the purpose of illustration, this load is modelled as an uncertain variable with a Lognormal distribution having a characteristic value of 34 kN/m^2 and a coefficient of variation of 10%. Further the "key elements" are considered to be the column elements in the structure.

All properties pertaining to the structural steel – yield strength, ultimate tensile strength and modulus of elasticity are modelled as uncertain variables using the modelling approach and data in the JCSS Probabilistic Model Code (JCSS, 2001) and are given in Table 1.

Using the above defined loads, resistances and material properties, the column sections are designed to resist combined bending and axial load effects for an annual target reliability index value of 4.7: this being the recommended minimum value for a reliability class RC2 structure in Eurocode – Basis of Structural Design (BS EN 1990:2002). A built-up square section of size 200 mm is obtained for the column elements. The thickness of the column plates is chosen to vary from 10 mm (in the upper storeys) to 25 mm (in the lower storeys), due to the varying intensity of the load to be carried.

2 Analysis and Discussion of Results

2.1 Approach and Parameters for analysis

Different exposure and damage events affecting the structure are considered for analysis. The extraordinary exposure event considered is an explosion modelled in the form of a lateral uniformly distributed load acting on the structural frame. Damage to a structural element is defined as i) the formation of a potential yield hinge or ii) exceedance of axial load carrying capacity resulting in effects such as buckling; for simplicity, this damage is assumed to be associated with failure of the element. Depending on the degree of ductility (1 being perfectly ductile and 0 being perfectly brittle), a damaged element maintains its load carrying capacity after damage if it is perfectly ductile and loses its entire load carrying capacity after damage if it is perfectly brittle.

The following four parameters are considered for analysis and different scenarios are generated depending on different combinations of the parameter values.

i) *Intensity of load from exposure event* – Three characteristic values are considered for the lateral uniformly distributed load – the base value of 34 kN/m^2, 51 kN/m^2 (1.5 times the base value) and 102 kN/m^2 (3 times the base value). For simplicity, the load intensities of these three cases are denoted as 1, 1.5 and 3 respectively. The base value of 34 kN/m^2 corresponds to the characteristic value for the Lognormal distribution chosen earlier for the designed "unidentified accidental load". The coefficient of variation of these load cases is taken as 10%. These exposure events can be termed as "extraordinary" load scenarios as their probability of occurrence is very small. This is in contrast to "ordinary" load scenarios (such as those involving imposed loads) which typically occur with a probability equal to 1 but with uncertain intensity.

ii) *Degree of ductility of elements* – Three possibilities are considered and these correspond to degree of ductility values of 1 (perfectly ductile), 0.5 (partially ductile) and 0 (perfectly brittle).

iii) *Storey(s) where damaged elements are located* – Three situations are considered and these are: (The actual number and location of the damaged columns on the affected storey(s) is specified in iv) below.)

- Columns damaged on the ground storey
- Columns damaged on the ground, 1st and 2nd storeys
- Columns damaged on the 5th, 6th, 7th, 8th, 9th and 10th storeys

iv) *Location of damaged elements with respect to orientation in the structural frame* – Two possibilities as listed below are considered:

- End column, next-to-end column and next-to-center column, all to the left of the center column
- Center column and next-to-center columns on either side of the center column

When an extraordinary exposure event occurs, it is possible that any damage occurring in the slab elements of the frame could then lead to possible failure of the structure. The assumption made here is that damage to the column elements of the structural frame is more likely to occur compared to damage to the slab elements; hence damage events corresponding to column damage are considered as the possible structural system failure initiating scenarios.

For each scenario, the system reliability index (and hence the system probability of failure) is determined using the β-unzipping method (Thoft-Christensen and Murotsu, 1986). The index of robustness (I_{ROB}) as defined in Baker *et al.* (2008) is then used to obtain an estimate of the robustness of the structure. Since specific exposure and damage events are considered, the index of robustness in such cases is computed conditional on the specified exposure and damage events. The probabilities corresponding to exposure and damage events are no longer required as these events are fixed and the conditional index of robustness is hence obtained as:

$$I_{ROB}|D,E = \frac{R_{DIR}}{R_{DIR}+R_{IND}} = \frac{C_{DIR}}{C_{DIR}+P(F|D,E)C_{IND}} \tag{1}$$

where:

$I_{ROB}|D,E$ is the index of robustness conditioned on the occurrence of specified exposure event(s) followed by specified damage event(s),

R_{DIR} and R_{IND} are the direct risks and indirect risks respectively,

R_{DIR} and R_{IND} are the associated direct consequences and indirect consequences respectively,

and $P(F|D,E)$ is the corresponding probability of system failure.

The index takes values between zero and one depending upon the source of risk. When there is no risk due to indirect consequences, the index of robustness equals one and the structural system is regarded to be completely robust.

The magnitude of direct consequences as a percentage of total reconstruction costs is estimated for the 3 cases defined in iii) above as 2, 5 and 10 respectively. The indirect consequences are determined based on the data and estimates given in a report on the failure of the twin towers of the World Trade Center in the USA in 2001 (Faber *et al.*, 2004). This report estimated the total consequences associated with the failure of the twin towers to be between 7.6 to 19.7 times the reconstruction costs of the towers. Using the lower bound of this estimate, the ratio of the indirect consequences to direct consequences is estimated to be 379, 151 and 75 respectively for the 3 cases defined in iii) above.

2.2 Analysis – Effect of intensity of load from extraordinary exposure event

Figure 2 shows the variation of the index of robustness with the intensity of the load from the extraordinary exposure event for different scenarios of damage to column elements (the cross marks on the structural frame indicate the damaged elements). The degree of ductility is taken to be the same (equal to 1) for all the plotted cases. When the intensity of the extraordinary exposure load is 1, the index of robustness is seen to be very close to one for all damage scenarios. As the intensity of the exposure load increases, the index of robustness decreases generally and a variation across the 6 damage scenarios becomes increasingly pronounced. For an intensity of 3, the damage scenario with the lowest index of robustness is the one with damaged column elements (end column, next-to-end column and next-to-center column) at the ground storey; this is because of the relatively high probability of failure due to the abnormally high exposure load and also the extremely high ratio of indirect consequences to direct consequences.

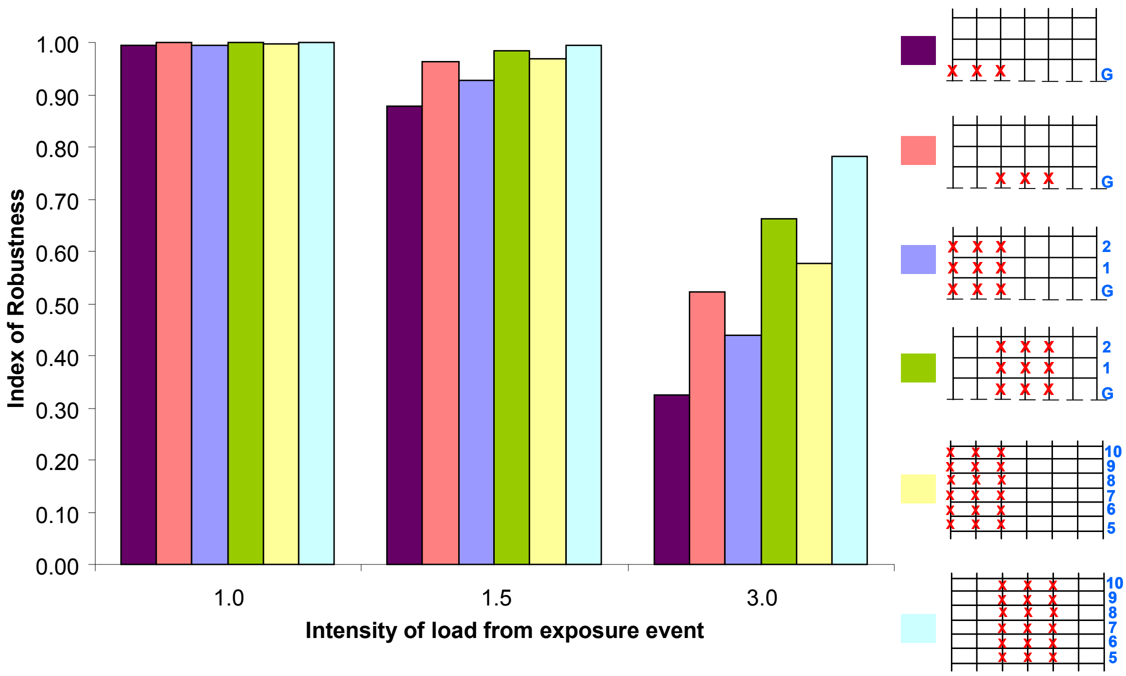

Figure 2. Variation of the index of robustness with the intensity of load from the extraordinary exposure.

2.3 Analysis – Effect of degree of ductility of elements

The variation of the index of robustness with the degree of ductility of the elements is plotted in Figure 3 for different scenarios of damage to column elements (the cross marks on the structural frame indicate the damaged elements). All the plotted cases correspond to the extraordinary load scenario with an intensity of 1.5. As the degree of ductility increases from 0 (perfectly brittle) to 1 (perfectly ductile), it is apparent that the index of robustness also increases as the contribution of the damaged elements to load redistribution after damage increases. For all the 6 damage scenarios plotted, the difference in the index of robustness values for degree of ductility values of 0 and 0.5 is seen to be much higher than that for degree of ductility values of 0.5 and 1. This implies the existence of a possible limit beyond which an increase in ductility leads to a little or no increase in robustness.

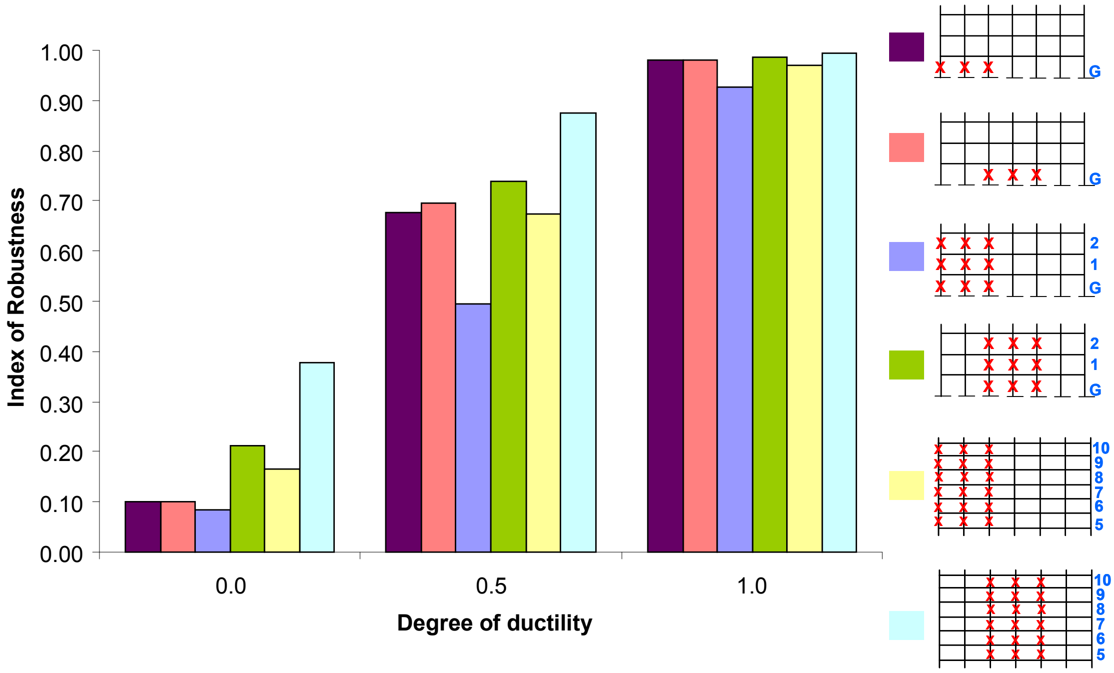

Figure 3. Variation of the index of robustness with the degree of ductility of elements.

2.4 Analysis – Effect of storey(s) where damaged elements are located

The effect of storey(s) where damaged elements are located on the index of robustness can be seen in Figure 4 for different scenarios of damage to column elements and different values of the degree of ductility (the cross marks on the structural frame indicate the damaged elements). All the plotted cases correspond to the extraordinary load scenario with an intensity of 1.5. When the degree of ductility is 0, the scenario where the damaged column elements are located on the ground storey is seen to be the least robust; this is due to the relatively similar probabilities of system failure for all the scenarios in this case coupled with the extremely high ratio of indirect consequences to direct consequences in this scenario. As the degree of ductility increases to 0.5, a relatively wide variation in the index of robustness values is seen; in this case, the scenario where the damaged column elements are situated on the ground, 1st and 2nd storeys is seen to have the least robustness; the increasing variation in the probabilities of system failure for the different scenarios here balances the high ratio of indirect consequences to direct consequences. When the degree of ductility is 1, the index of robustness is seen to be almost insensitive to the effect of the storey(s) where damaged elements are located; this can be attributed to the relatively low probability of system failure due to the maximum possible contribution of the damaged elements in the load redistribution process after damage.

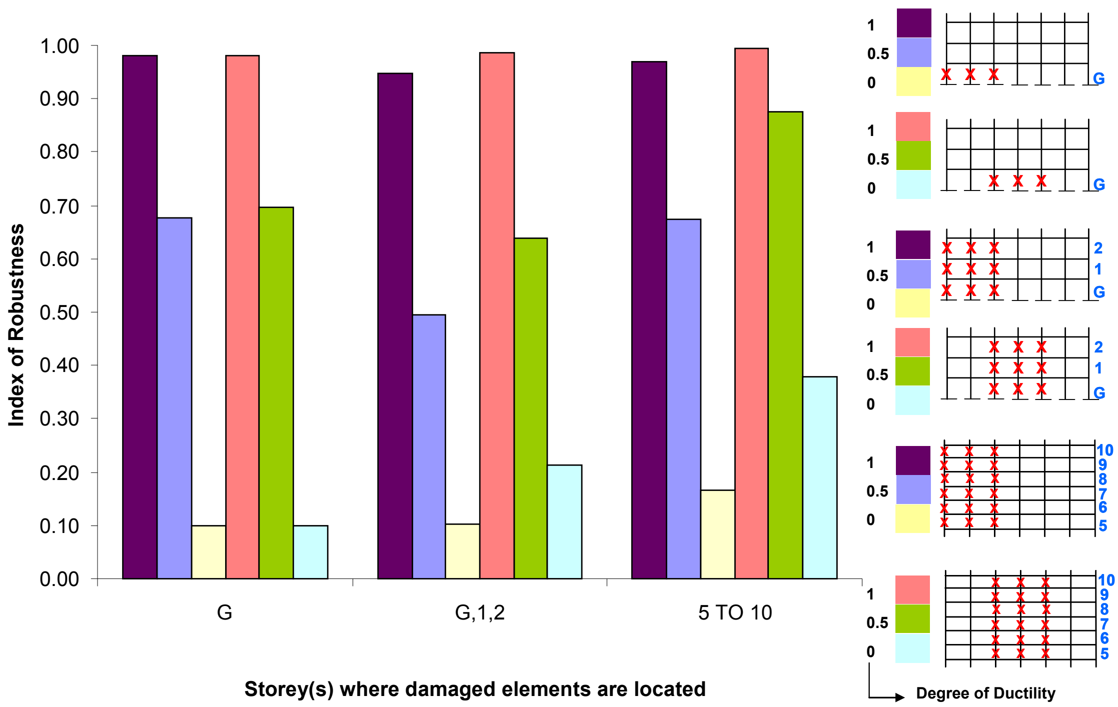

Figure 4. Variation of the index of robustness with the location of storey(s) where damaged elements are located

2.5 Analysis – Effect of location of damaged elements with respect to orientation in the structural frame

In Figure 5, the variation of the index of robustness with the location of damaged elements with respect to orientation in the structural frame is shown for different scenarios of damage to column elements and different values of the degree of ductility (the cross marks on the structural frame indicate the damaged elements). All the plotted cases correspond to the extraordinary load scenario with an intensity of 1.5. It is seen consistently that the scenarios where the damaged elements are the end column, next-to-end column and next-to-center column (all to the left of the center column) have lower index of robustness values than the scenarios where the damaged elements are the center column and next-to-center columns on either side of the center column. This can be due to the geometrically favourable configuration for load redistribution after damage that emerges in the latter case where the damaged elements are located in the center of the structural frame as opposed to the former case where the damaged elements are located in one end of the frame.

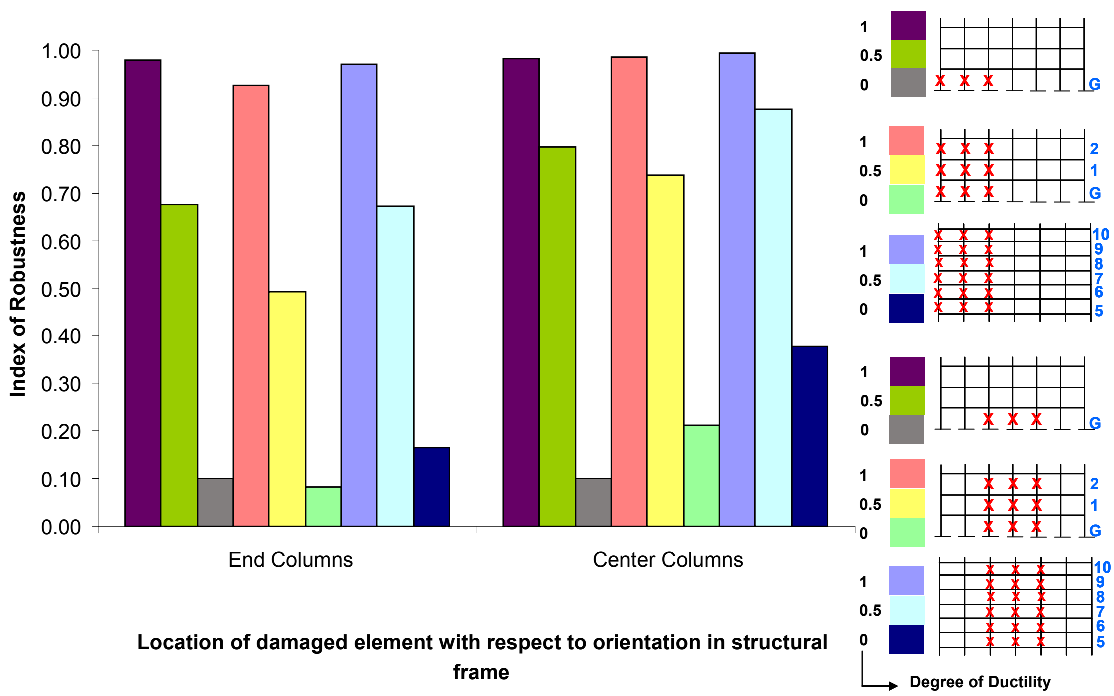

Figure 5 Variation of the index of robustness with the location of damaged elements with respect to orientation in structural frame.

3 References

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