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INTRODUCTION TO LIMIT STATES

1.0 INTRODUCTION

A Civil Engineering Designer has to ensure that the structures and facilities he designs are (i) fit for their purpose (ii) safe and (iii) economical and durable. Thus safety is one of the paramount responsibilities of the designer. However, it is difficult to assess at the design stage how safe a proposed design will actually be – consistent with economy. There is, in fact, a great deal of uncertainty about the many factors, which influence both safety and economy. Firstly, there is a natural variability in the material strengths and secondly it is impossible to predict the loading, which a structure (e.g. a building) may be subjected to on a future occasion. Thus uncertainties affecting the safety of a structure are due to

- uncertainty about loading
- uncertainty about material strength and
- uncertainty about structural dimensions and behaviour.

These uncertainties together make it impossible for a designer to guarantee that a structure will be absolutely safe. All that the designer could ensure is that the risk of failure is extremely small, despite the uncertainties.

An illustration of the statistical meaning of safety is given in Fig. 1. Let us consider a structural component (say, a beam) designed to carry a given nominal load. Bending moments (B.M.) produced by characteristic loads are first computed. These are to be compared with the characteristic resistance or strength (R.M.) of the beam. But the characteristic resistance (R.M.) itself is not a fixed quantity, due to variations in material strengths that might occur between nominally same elements. The actual resistance of these elements can be expected to vary as a consequence. The statistical distribution of these member strengths (or resistances) will be as sketched in (*a*).

Similarly, the variation in the maximum loads and therefore load effects (such as bending moment) which different structural elements (all nominally the same) might encounter in their service life would have a distribution shown in (*b*). ***The uncertainty here is both due to variability of the loads applied to the structure, and also due to the variability of the load distribution through the structure.*** Thus if a particularly weak structural component is subjected to a heavy load which exceeds the strength of the structural component, clearly failure could occur.

Unfortunately it is not practicable to define the probability distributions of loads and strengths, as it will involve hundreds of tests on samples of components. Normal design calculations are made using a single value for each load and for each material property and making appropriate safety factor into the design calculations. The value used is termed as "***Characteristic Strength or Resistance***" or " ***Characteristic Load***".

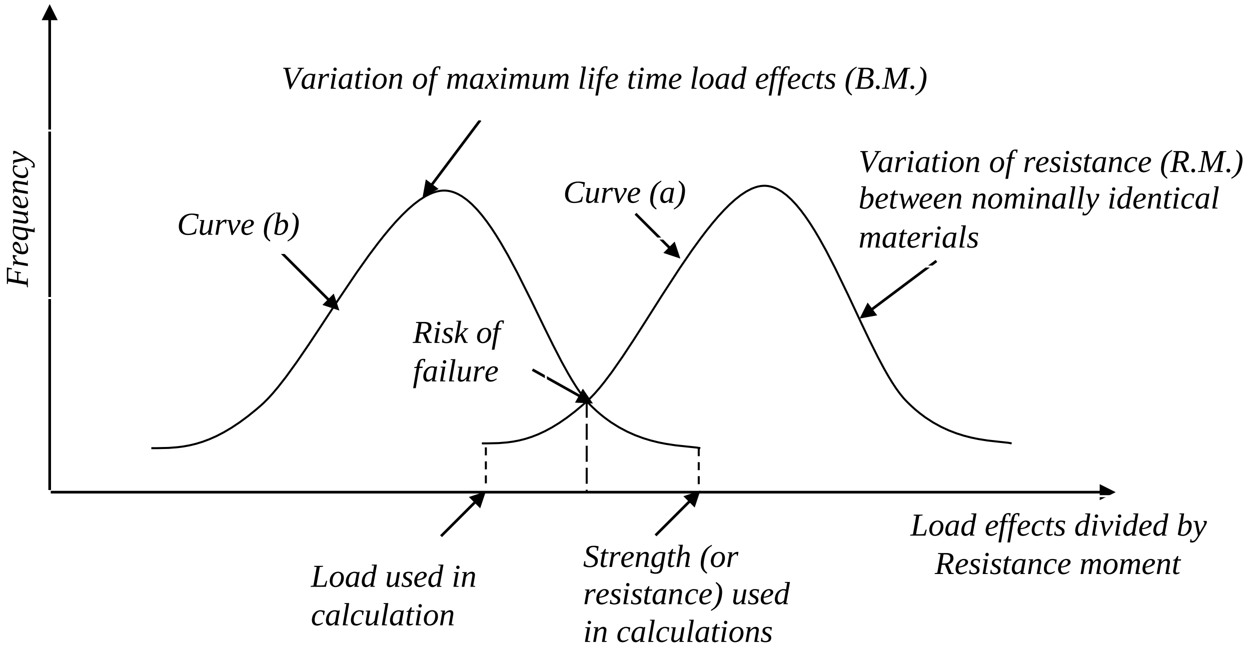

Fig. 1 Statistical Meaning of Safety

Characteristic resistance of a material (such as Concrete or Steel) is defined as that value of resistance below which not more than a prescribed percentage of test results may be expected to fall. (For example the characteristic yield stress of steel is usually defined as that value of yield stress below which not more than *5%* of the test values may be expected to fall). In other words, this strength is expected to be exceeded by *95%* of the cases.

Similarly, ***the characteristic load is that value of the load, which has an accepted probability of not being exceeded during the life span of the structure.*** Characteristic load is therefore that load which will not be exceeded *95%* of the time.

2.0 STANDARDISATION

Most structural designs are based on experience. Standardisation of all designs is unlikely within the foreseeable future hence design rules, based on experience, become useful. If a similar design has been built successfully elsewhere, there is no reasons why a designer may not consider it prudent to follow aspects of design that have proved successful, and adopt standardised design rules. As the consequences of bad design can be catastrophic, the society expects designers to explain their design decisions. It is therefore advantageous to use methods of design that have proved safe in the past. Standardised design methods can help in comparing alternative designs while minimising the risk of the cheapest design being less safe than the others.

Most Governments attempt to ensure structural safety through regulations and laws. Designers then attempt to achieve maximum economy within the range of designs that the regulations allow. Frequently the professions are allowed to regulate themselves; in these a cases the Regulations or ***Codes of Practices*** are evolved by consultation and consensus within the profession.

3.0 ALLOWABLE STRESS DESIGN (ASD)

With the development of linear elastic theories in the 19^{th} century the stress-strain behaviour of new materials like wrought iron & mild steel could be accurately represented. These theories enabled indeterminate structures to be analysed and the distribution of bending and shear stresses to be computed correctly. The first attainment of yield stress of steel was generally taken to be the onset of failure. The limitations due to non-linearity and buckling were neglected.

The basic form of calculations took the form of verifying that the stresses caused by the characteristic loads must be less than an "***allowable stress***", which was a fraction of the yield stress. Thus the allowable stress may be defined in terms of a "***factor of safety***" which represented a margin for overload and other unknown factors which could be tolerated by the structure. The allowable stress is thus directly related to yield stress by the following expression:

$$Allowable\,stress = \frac{Yield\ stress}{Factor\,of\ safety}$$

In general, each member in a structure is checked for a number of different combinations of loading. The value of factor of safety in most cases is taken to be around 1.67. Many loads vary with time and these should be allowed for. It is unnecessarily severe to consider the effects of all loads acting simultaneously with their full design value, while maintaining the same factor of safety or safety factor. Using the same factor of safety or safety factor when loads act in combination would result in uneconomic designs.

A typical example of a set of load combinations is given below, which accounts for the fact that the dead load, live load and wind load are all unlikely to act on the structure simultaneously at their maximum values:

(Stress due to dead load + live load) < allowable stress
(Stress due to dead load + wind load) < allowable stress
(Stress due to dead load + live load + wind) < 1.33 times allowable stress.

In practice there are severe limitations to this approach. These are the consequences of material non-linearity, non-linear behaviour of elements in the post-buckled state and the ability of the steel components to tolerate high theoretical elastic stresses by yielding locally and redistributing the loads. Moreover the elastic theory does not readily allow for redistribution of loads from one member to another in a statically indeterminate structures.

4.0 LIMIT STATE DESIGN

An improved design philosophy to make allowances for the shortcomings in the **“*Allowable Stress Design*”** was developed in the late *1970*’s and has been extensively incorporated in design standards and codes formulated in all the developed countries. Although there are many variations between practices adopted in different countries the basic concept is broadly similar. The probability of operating conditions not reaching failure conditions forms the basis of “***Limit States Design***” adopted in all countries.

“Limit States" are the various conditions in which a structure would be considered to have failed to fulfil the purpose for which it was built. In general two limit states are considered at the design stage and these are listed in Table 1.

Table 1: Limit States

Ultimate Limit State	Serviceability Limit State
Strength (yield, buckling)	Deflection
Stability against overturning and sway	Vibration
Fracture due to fatigue	Fatigue checks (including reparable damage due to fatigue)
Brittle Fracture	Corrosion

“Ultimate Limit States” are those catastrophic states, which require a larger reliability in order to reduce the probability of its occurrence to a very low level. “Serviceability Limit State" refers to the limits on acceptable performance of the structure.

Not all these limits can be covered by structural calculations. For example, corrosion is covered by specifying forms of protection (like painting) and brittle fracture is covered by material specifications, which ensure that steel is sufficiently ductile.

5.0 PARTIAL SAFETY FACTOR

The major innovation in the new codes is the introduction of the partial safety factor format. A typical format is described below:

In general calculations take the form of verifying that

$S^* \leq R^*$

where S^* is the calculated factored load effect on the element (like bending moment, shear force etc) and R^* is the calculated factored resistance of the element being checked, and is a function of the nominal value of the material yield strength.

S^* is a function of the combined effects of factored dead, live and wind loads.
(Other loads – if applicable, are also considered)

In accordance with the above concepts, the safety format used in Limit State Codes is based on probable maximum load and probable minimum strengths, so that a consistent level of safety is achieved. Thus, the design requirements are expressed as follows:

$$S_d \le R_d$$

where S_d = Design value of internal forces and moments caused by the design Loads, F_d
$F_d = \gamma_f$ * Characteristic Loads.
γ_f = a load factor which is determined on probabilistic basis

$$R_d = \frac{\text{Characteristic Value of Resistance}}{\gamma_m}$$

where γ_m = a material factor, which is also determined on a '*probabilistic basis*'

It should be noted that γ_f makes allowance for possible deviation of loads and the reduced possibility of all loads acting together. On the other hand γ_m allows for uncertainties of element behaviour and possible strength reduction due to manufacturing tolerances and imperfections in the material.

Collapse is not the only possible failure mode. Excessive deflection, excessive vibration, fracture etc. also contribute to Limit States. Fatigue is an important design criterion for bridges, crane girders etc. (These are generally assessed under serviceability Limit States)

Thus the following limit states may be identified for design purposes:

- Ultimate Limit State is related to the maximum design load capacity under extreme conditions. The partial load factors are chosen to reflect the probability of extreme conditions, when loads act alone or in combination.
- Serviceability Limit State is related to the criteria governing normal use. Unfactored loads are used to check the adequacy of the structure.
- Fatigue Limit State is important where distress to the structure by repeated loading is a possibility.

The above limit states are provided in terms of partial factors, reflects the severity of the risks.

An illustration of partial safety factors suggested in the revised IS: 800 for ultimate load conditions is given in Table 2.

Table 2*: *Partial safety factors (According to proposed revisions to IS: 800)

Loading	γ_f		
	DL	***LL***	***WL***
Dead Load (unfavourable effects)	1.35	-	-
Dead load restraining uplift or overturning	1.0	-	-
Imposed Load + Dead Load	1.35	1.5	-
Dead Load + Wind Load	1.35	-	1.5
Dead Load + Imposed Load + wind Load (Major Load)	1.35	1.05	1.5
Dead Load + Imposed Load (Major Load) + wind Load	1.35	1.5	1.05

Requirements for all Buildings to maintain Structural integrity are given below:

Structures should remain as complete integral units even when (due to an accident such as explosion) one of the members fail or become inoperative. This requirement provides a significant measure of safety for the occupants and is termed "Structural integrity requirement".

The buildings should be effectively tied together at each principal floor and roof level, in both directions. The recommended minimum tie strengths are *75 kN* at floor level, *40 kN* at roof level. Each section between expansion joints should be treated as a separate building. These requirements are aimed at ensuring that the collapse of one element of a structure does not trigger the failure of the structure as a whole. By tying the structure together, it is possible to ensure that there is an alternative load path that would help to enhance safety.

Suggested requirements for integrity of buildings of five storeys or more are given below:

- For sway resistance, no portion of structures should be dependent on only one bracing system.
- The minimum tie strengths to be provided are $0.5\ W_f\ S_t\ L_a$ internally and $0.25\ W_f\ S_t\ L_a$ externally.
  W_f - total factored load / unit area
  S_t - tie spacing
  L_a - distance between columns in the direction
- At the edge of the structure, columns should be restrained by horizontal ties resisting *1%* of column load.
- Columns should be continuous vertically through the floors, as far as possible.
- Collapse must not be disproportionate and the role of key elements should be identified.
- Precast floors must be anchored at both ends.

6.0 CONCLUDING REMARKS

This chapter reviews the provisions of safety, consequent on uncertainties in loading and material properties. The partial load factors employed in design to take into account these variations are discussed and illustrated.

7.0 REFERENCES

1. Owens G.W., Knowles P.R : "Steel Designers Manual", The Steel Construction Institute, Ascot, England, 1994
2. British Standards Institution : "BS 5950, Part-1 Structural use of steelwork in building", British Standards Institution, London, 1985

Structural Steel Design Project **Calculation Sheet**	Job No:	Sheet ***1 of 2***	Rev
	Job Title: *MAXIMUM FACTORED LOADS*		
	Worked Example - 1		
		Made by *SSSR*	Date *15-09-99*
		Checked by *RN*	Date *20-09-99*

A frame sketched in Fig. 2 is loaded by a dead load of 6 kN/m, imposed load of 20 kN/m and wind load of 10 kN/m. The example below illustrates the checks in respect of the following.

- *Imposed load + Dead load*
- *Wind load + Dead load*
- *Imposed load + Wind load + Dead load*

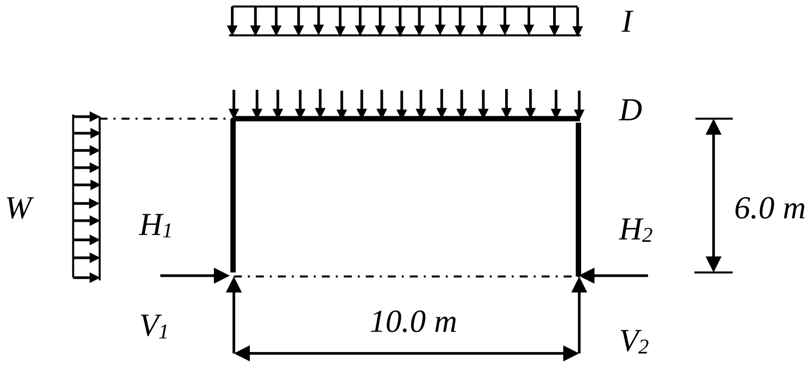

Fig. 2 Portal frame subject to loading

Dead Load (D) 6 kN/m

Imposed Load (I) 20 kN/m

Wind Load (W) 10 kN/m

Case1 - Dead plus imposed loads

$$V_1 = V_2 = (1.5I + 1.35D) * span/2$$
$$= (1.5 * 20 + 1.35 * 6) * 5 = 190.5 \text{ kN}$$

$\gamma_{fDL} = 1.35$
$\gamma_{fIL} = 1.50$

Structural Steel Design Project

Calculation Sheet

Job No:

Sheet **2 of 2**

Rev

Job Title: *MAXIMUM FACTORED LOADS*

Worked Example - 1

Made by *SSSR*

Date *15-09-00*

Checked by *RN*

Date *20-09-99*

Case 2 - Dead plus wind

Taking moments about right support,

$\gamma_{fDL} = 1.35$

$\gamma_{fWL} = 1.50$

$V_1 = [1.35\ D\ span^2 / 2 - 1.50\ W * height^2/2]\ 1/10$

$= [1.35 * 6 * 100/2 - 1.50 * 10 * 36/2]\ 1/10$

$= 13.5\ kN$

$V_2 = 1.35D * span - V_1$

$= 1.35 * 6 * 10 - 13.5 = 67.5\ kN$

$H_1 + H_2 = 1.35\ W * height = 1.50 * 10 * 6 = 90\ kN$

(Note: The evaluation of H_1 and H_2 will depend on the stiffnesses of the members as the problem is statically indeterminate)

Case 3 - Dead plus imposed plus wind

$\gamma_{fDL} = 1.35$

$\gamma_{fIL} = 1.50$

$\gamma_{fWL} = 1.05$

$V_1 = 1.35 * D * span/2 + 1.5 * I * span/2 - 1.05 * W * height^2 / (2 * span)$

$= 1.35 * 6 * 5 + 1.5 * 20 * 5 - 1.05 * 10 * 36/20$

$= 171.6\ kN$

$V_2 = 1.35 * D * span/2 + 1.5 * I * span/2 + 1.05 * W * height^2/2 * span$

$= 1.35 * 6 * 5 + 1.5 * 20 * 5 + 1.05 * 10 * 36/20$

$= 209.4\ kN$

The worst value for design purposes are;

$V_1 = 190.5\ kN ;\ V_2 = 209.4\ kN$