4 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 <u>not</u> 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***".

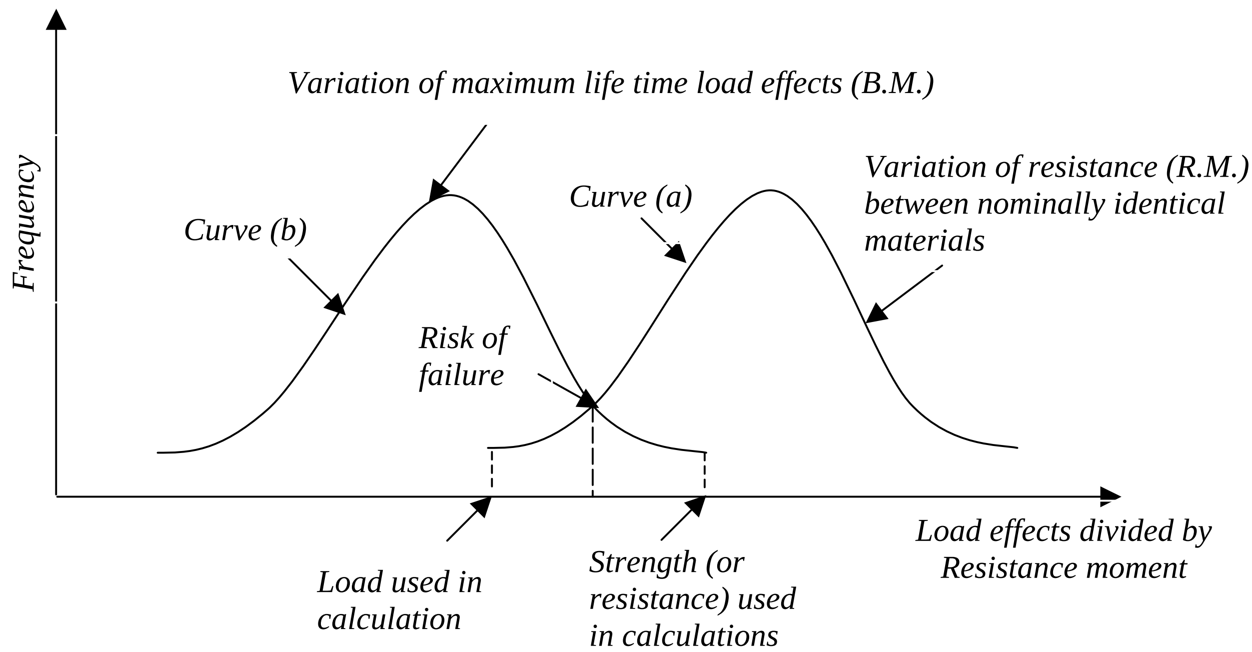

Fig. 1 Statistical Meaning of Safety

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 <u>not</u> 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 *19th* 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

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

"Limit State of Strength" are: loss of equilibrium of the structure and loss of stability of the structure. "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:

$S_d \leq R_d$

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 for applied load and materials as suggested in the revised IS: 800 for Limit States of Strength and Limit States of Serviceability are given in Table 2 and 3 respectively.

Table 2*: *Partial safety factors

Combination	Limit State of Strength					Limit state of Serviceability			
	DL	**LL’**		**WL/ EL**	**AL**	**DL**	**LL’**		**WL/ EL**
		Leading	Accompanying				Leading	Accompanying	
DL+LL+CL	1.5	1.5	1.05	—	—	1.0	1.0	1.0	—
DL+LL+CL+ WL/EL	1.2 1.2	1.2 1.2	1.05 0.53	0.6 1.2	—	1.0	0.8	0.8	0.8
DL+WL/EL	1.5 (0.9)*	—	—	1.5	—	1.0	—	—	1.0
DL+ER	1.2 (0.9)	1.2	—	—	—	—	—	—	—
DL+LL+AL	1.0	0.35	0.35	—	1.0	—	—	—	—

* This value is to be considered when the dead load contributes to stability against overturning is critical or the dead load causes reduction in stress due to other loads.

‘ When action of different live loads is simultaneously considered, the leading live load is whichever one causes the higher load effects in the member/section.

Abbreviations: DL= Dead Load, LL= Imposed Load (Live Loads), WL= Wind Load,
CL= Crane Load (Vertical/horizontal), AL=Accidental Load,
ER= Erection Load, EL= Earthquake Load.

Table 3*: *Partial safety factors

Sl. No.	Definition	Partial Safety Factor	
1	Resistance, governed by yielding γ_{m0}	1.10	
2	Resistance of member to buckling γ_{m0}	1.10	
3	Resistance, governed by ultimate stress γ_{m1}	1.25	
4	Resistance of connection γ_{m1}	Shop Fabrications	Field Fabrications
	(i) Bolts-Friction Type, γ_{mf}	1.25	1.25
	(ii) Bolts-Bearing Type, γ_{mb}	1.25	1.25
	(iii) Rivets, γ_{mr}	1.25	1.25
	(iv) Welds, γ_{mw}	1.25	1.50

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 FACTORS GOVERNING THE ULTIMATE STRENGTH

Stability is generally ensured for the structure as a whole and for each of its elements. This includes overall frame stability against overturning and sway, as given below. The structure as a whole or any part of it are designed to prevent instability due to overturning, uplift or sliding under factored load as given below:

a) The actions are divided into components aiding instability and components resisting instability.

b) The permanent and variable actions and their effects causing instability are combined using appropriate load factors as per the Limit States requirements to obtain maximum destabilizing effect.

c) The permanent actions (loads) and effects contributing to resistance shall be multiplied with a partial safety factor 0.9 and added together with design resistance (after multiplying with appropriate partial safety factor). Variable actions and their effects contributing to resistance are disregarded

d) The resistance effect shall be greater than or equal to the destabilizing effect. Combination of imposed and dead loads should be such as to cause most severe effect on overall stability.

7.0 LIMIT STATE OF SERVICEABILITY

As stated in IS: 800, Serviceability Limit State is related to the criteria, governing normal use. Serviceability limit state is limit state beyond which service criteria, specified below, are no longer met:

a) Deflection Limit
b) Vibration Limit
c) Durability Consideration
d) Fire Resistance

Load factor, $\gamma_{f,}$ of value equal to unity are used for all loads leading to Serviceability Limit States to check the adequacy of the structure under serviceability limit states, unless specified otherwise.

The deflection under serviceability loads of a building or a building component should be such that, they do not impair the strength of the structure or components or cause damage to finishing. Deflections are to be checked for the most adverse but realistic combination of service loads and their arrangement, by elastic analysis, using a load factors as per Table 3. Table 4 gives recommended limits of deflections for certain structural members and systems.

As per IS: 800, suitable provisions in the design are required to be made for the dynamic effects of live loads, impact loads and vibration due to machinery operating loads. In severe cases possibility of resonance, fatigue or unacceptable vibrations shall be investigated. Unusually flexible structures (generally the height to effective width of lateral load resistance system exceeding 5:1) need to be investigated for lateral vibration under dynamic wind loads. Structures subjected to large number of cycles of loading shall be designed against fatigue failure as discussed in Chapter 2.

Durability or Corrosion resistance of a structure is generally, under conditions relevant to their intended life as are listed below:

a) The environment
b) The degree of exposure
c) The shape of the member and the structural detail
d) The protective measure
e) Ease of maintenance

Fire resistance of a steel member is a function of its mass, its geometry, the actions to which it is subjected, its structural support condition, fire protection measures adopted and the fire to which it is exposed. Design provisions to resist fire are briefly discussed in Chapter 2.

Table 4: ***Partial safety factors [According to IS: 800 (2007)]***

Type of Building	Deflection	Design Load	Member	Supporting	Maximum Deflection
Industrial building	Vertical	Live load/Wind load	Purlins and Girts Purlins and Girts	Elastic cladding Brittle cladding	Span / 150 Span / 180
		Live load Live load	Simple span Simple span	Elastic cladding Brittle cladding	Span / 240 Span / 300
		Live load Live load	Cantilever span Cantilever span	Elastic cladding Brittle cladding	Span / 120 Span / 150
		Live load or Wind load	Rafter supporting	Profiled Metal Sheeting	Span / 180
				Plastered Sheeting	Span / 240
		Crane load (Manual operation)	Gantry	Crane	Span / 500
		Crane load (Electric operation up to 50 *t*)	Gantry	Crane	Span / 750
		Crane load (Electric operation over 50 *t*)	Gantry	Crane	Span / 1000
	Lateral	No cranes	Column	Elastic cladding	Height / 150
		No cranes	Column	Masonry/Brittle cladding	Height / 240
		Crane + wind	Gantry (lateral)	Crane(absolute)	Span / 400
				Relative displacement between rails	10 mm
		Crane+ wind	Column/frame	Gantry (Elastic cladding; pendent operated)	Height / 200
			Column/frame	Gantry (Brittle cladding; cab operated)	Height / 400
Other Buildings	Vertical	Live load	Floor & Roof	Elements not susceptible to cracking	Span / 300
		Live load	Floor & Roof	Elements susceptible to cracking	Span / 360
		Live load	Cantilever	Elements not susceptible to cracking	Span / 150
		Live load		Elements susceptible to cracking	Span / 180
	Lateral	Wind	Building	Elastic cladding Brittle cladding	Height / 300 Height / 500
		Wind	Inter storey drift	---	Storey height / 300

8.0 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.

9.0 REFERENCES

1. Owens G.W., Knowles P.R : "Steel Designers Manual", The Steel Construction Institute, Ascot, England, 1994
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3. IS: 800 (2007), General Construction in Steel – Code of Practice, Bureau of Indian Standards, New Delhi, 2007.

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*

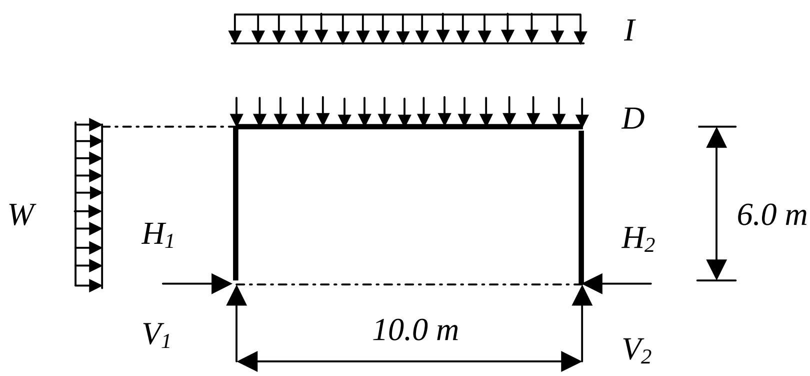

Fig. 2 Portal frame subject to loading

Dead Load (D) 6 kN/m

Imposed Load (I) 20 kN/m

Wind Load (W) 10 kN/m

Case 1- Dead plus imposed loads

$$V_1 = V_2 = (1.50\, l + 1.50\, D) * span/2$$
$$= (1.50 * 20 + 1.50 * 6) * 5 = 195.0 kN$$

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

Structural Steel Design Project	Job No:	Sheet **2 of 2**	Rev
	Job Title: *MAXIMUM FACTORED LOADS*		
	Worked Example - 1		
		Made by *SSSR*	Date *15-09-00*
Calculation Sheet		Checked by *RN*	Date *20-09-99*

Case 2 - Dead plus wind

Taking moments about right support,

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

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

$= 18.0$ kN

$\gamma_{fDL} = 1.50$
$\gamma_{fWL} = 1.50$

$V_2 = 1.50\ D * span - V_1$

$= 1.50 * 6 * 10 - 18.0 = 72.0$ kN

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

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

Case 3 - Dead plus imposed plus wind

$V_1 = 1.20 * D * span /2 + 1.20 * I * span/2 - 1.20 * W * height^2 / (2 * span)$

$= 1.20 * 6 * 5 + 1.20 * 20 * 5 - 1.20 * 10 * 36/20$

$= 134.4$ kN

$\gamma_{fDL} = 1.35$
$\gamma_{fIL} = 1.50$
$\gamma_{fWL} = 1.05$

$V_2 = 1.20 * D * span /2 + 1.20 * I * span/2 + 1.20 * W * height^2/2 * span$

$= 1.20 * 6 * 5 + 1.20 * 20 * 5 + 1.20 * 10 * 36/20$

$= 177.6$ kN

The worst value for design purposes are;

$V_1 = 195.0$ kN ; $V_2 = 177.6$ kN