RESEARCH ARTICLE OPEN ACCESS

Limit State Design: IS: 800 2007 a New Challenge for Structural Engineers in India

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ABSTRACT
Since last two decades Limit State concept of Design (LSD) of steel structure has been adopted by the structural engineers worldwide. In India it is still a new concept for the practicing structural engineers as the formal publication of IS 800-2007 was made in Dec, 2007, only seven years back. As a result Indian engineers are to face a real challenge to cover-up the gap in between. Publication of ISO: 2943 in 90's is a mile stone of global acceptance of LSD. Revision of IS 800-1984 to IS: 800: 2007 is made for a complete change of concept of design hitherto followed. Implementation of LSD was a problem in all most all the countries in the world. India is also facing the same due to delayed introduction of LSD codes when the level of knowledge on limit state developed very fast internationally. Today it becomes an urgent task for the Indian structural engineers to study and review more and more the basic philosophy and concept in contrast to the traditional method of Working Stress Design (WSD) in a documented manner so that this can help everyone in this field for effective application of LSD in practical design. This paper will address this issue as why it becomes a real historical challenge for engineers in India. Here it will also be attempted to highlight the basic philosophical understanding required for successful transformation from the traditional concept to this new concept of LSD. Some comparative design review of both the codes will also be presented for practical understanding of the conceptual changes.
KEYWORDS: Steel Structure, IS:800, LSD, WSD, Reliability, Uncertainty.

I. INTRODUCTION

Since last half a century Indian engineers are traditionally habituated with Permissible Stress concept of design. Limit State Design (LSD) or Load Resistance Factor Design (LRFD–term used in U.S.) first contradicts the term 'permissible', the basic concept of erstwhile design. The word Permissible is now impermissible in LSD or LRFD method. Traditionally used term Factor of Safety (FoS) changes to Partial Safety Factor (PSF) is another major departure. Structure can respond to its demand up to fracture stress i.e. in an in-elastic regime rather than a nearly fictitious elastic regime as hitherto considered, is another major conceptual changes in understanding of failure modes. The truth, that the probability of failure of a structure cannot be avoided even if it is properly designed but the chance of failure shall be quantified as finite and to be kept in an acceptably low level. The practicing engineers sometime become confused and become skeptical in using LSD method by Using IS: 800-2007 instead of IS: 800-1984 and purpose of this code is not well understood all the times. As a result the adoption of this new code faces some hindrances which are truly unfortunate. From last 4 years LSD method in steel design is taught in almost all engineering institutions in India. But young graduate engineers after entering the industry in many cases are instructed by the seniors to design a structure with Traditional WSD (IS: 800-1984) method. It is true that IIT Madras, Insdag, other important institutions and some individuals are trying to develop some review documents and literature [4, 5, 28] on IS: 800-2007 including training to the professional and practicing engineers.

II. HISTORIC CHALLENGE

Inception of reliability based LSD concept was in early 1970. Based on continuous up gradation of knowledge on structure through, experience, testing and research, LSD (LRFD) method has evolved. Development of human knowledge is a continuous and uninterrupted process. A broad schematic diagram in Fig.1 shows how the level of engineering knowledge develops globally since early 20th century and development of national codes in India. In US, AISC 1986 was published by formally recognized reliability concept of design (LRFD). Indian code for Steel design and construction, IS 800 was first published in 1956 with subsequent revisions in 1962, 1968, 1984, and 2007, till publication of IS 800-2007.

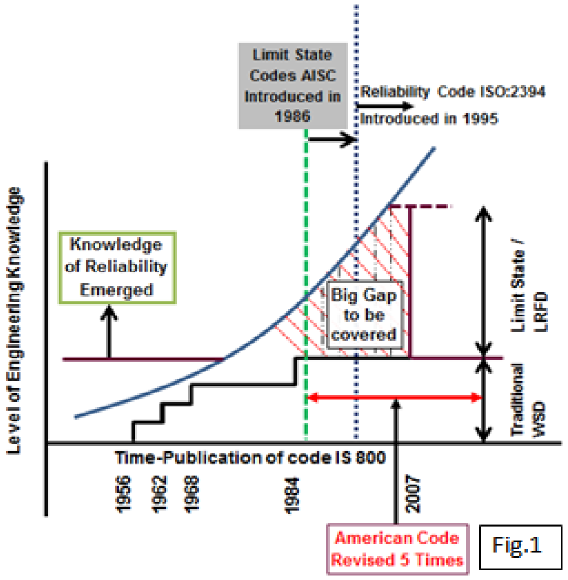


Fig.1

In India the engineers are practiced with traditional WSD method for such a long time that changing to a conceptually changed modern method is really a big challenge. Applicability of this LSD method, at its inception, in direct design, was a problem faced by practicing engineers in all most all the countries in the world but that phase has now been successfully overcame by the world community of engineers. ISO 2394 published in 90's which established that the reliability based LSD is the only method that shall be used by the structural engineers throughout the world. Indian engineers today require to fill the large knowledge gap already generated by the delayed introduction of LSD in steel in India. This is shown schematically in the Fig.1. Codification mean formal acceptance of knowledge shown in stepped lines and red shed area is the gap created for the knowledge on reliability method of design. At present stage, globally, reliability based design concept advances sharply to a very high level and that took place in last two decades. American LRFD code revised 5 times between 1986 and 2010 as given in Table-1. Up gradation of knowledge level may be a precondition for effective and wide adoption of IS 800-2007 in practical design in India. This is precisely the challenge. Merely acceptance of some more complex numerical methods as laid down in LSD codes may not lead to effective implementation of this modern design concept. To take this challenge the foremost work for real adoptability of LSD in direct design requires a basic philosophical and conceptual up-gradation of the traditional mind set of structural engineers. It requires continuous exchange between structural engineers on wider understanding and experience of direct design implementation of LSD concept with review and study.

Table-1: Revision of American codes: 5 times between 1986 to 2010 after first Publication of LSD (LRFD) code in 1986

September 1. 1986	-	Specification for structural steel buildings - Load and Resistance Factor Design
December 1, 1993	-	Load and Resistance Factor Design Specification for Structural Steel
December 27, 1999	-	LRFD Specification for Structural Steel Buildings
March 9, 2005	ANSI/AISC 360-05	Specification for Structural Steel Buildings
June 22, 2010	ANSI/AISC 360-10	Specification for Structural Steel Buildings

III. THE PHILOSOPHY

Application of Limit State concept in practical design is not only the adoption of some more complicated numerical formulation (in LSD) but to address all structural design problems through a new philosophical approach. The approach is basically probabilistic rather than fully deterministic, hitherto used by the practicing engineers [2]. Some confusion faced by the practicing structural engineers in implementing LSD method in practical design can be addressed effectively through a philosophical angle. First question that confront the structural designer today why and for what reason traditional WSD shall be rejected. Are the structures hitherto designed by this method are highly uneconomic or unsafe or non-performing? Why should a practicing structural engineers going to deal with more mathematical jargons in LSD than WSD? Will chance of human error in design calculation not be high if more complicated numerical methods as in LSD are used? Quality control measure in construction stage is generally not in the hand of a designer, how can he or she opt for more 'safe and economic design' without being confirmed with these issues? There are so many practical questions of this type come on the way of transition from traditional method to LSD method. The task of the structural engineer is to design a structure that can withstand load and strength demands throughout its expected lifetime. Structural engineers often have to take many decisions while designing a structure. Many of the decisions are not always fully confirmed even by the designer with the real world behavior of the structure. For example, a simply supported or fixed condition of a beam support if considered in design is merely an approximate idealization of the real word situation while exact behavior can be different. So an element of uncertainty always lies in the design work. Human being is always striving for knowledge to unfold the uncertainty in the nature. Uncertainty can only be reduced through development of knowledge by scientific research, observation and experience. Philosophically it can be said 'The only thing that is certain is that nothing is certain' [1] Reliability base design method (LSD/LRFD) recognizes this fact in a rational and quantitative way. Philosophical aspect of LSD can be summarized as follows:

3.1 Concept of failure of structure:

3.1.1 LSD recognized the truth that the probability of failure of a structure always exist however small it is, but finite. This probability of failure can be numerically calibrated to keep it in an acceptably low level by method of reliability based design. In traditional WSD, chance of failure was not conceptually accepted.

3.1.2 Hitherto, the structural design was based on a permissible format by limiting the failure mode well within an empirically defined elastic range, (Linear) irrespective of actual behavior of structure in a failure consequence. LSD considered the behavior of a structural member till its probable failure limit and predicted the routes towards failure by attempt to quantify different variables like type of load-permanent, quasi-permanent, transient accidental etc. and resistance like axial, bending, shear, torsion, buckling, bearing and so on.

3.1.3 It is recognized probabilistically that it will be very uneconomical or impossible to design a structure without any chance of failure. As there is very low but finite chance of failure of structure, a new concept of safety is emerging in LSD method to avoid immediate, progressive and disproportionate collapse of structure. Additional measures have been prescribed in many codes to identify the critical members, failure of which can destabilize the structural system. So, local and global, elastic and inelastic stability aspect has been given much more emphasis in this new format of design.

3.1.4 As the ultimate failure sometime occurs in inelastic-plastic regime beyond the limit of strain hardening (as can be observed in standard stress-strain curve of ductile steel) a failure limit of serviceability of structure is also included implicitly in LSD method of design to recognize the requirement of design intended performance limit of any structure.

3.2 Concept of Partial Safety Factor (PSF): Safety factor format is the most important conceptual changes incorporated in LSD format. As discussed, uncertainty underlying in the design assumption of random variables responsible for safety is varied inherently. Loads of different kind has different demand from the structure. Level of uncertainty varies for different loads. Structure responds through its resistance by its inherently varied nature of internal stresses. So the quantification of uncertainty will vary and there must be different risk factor. PSF concept developed to recognize the real world truth. Moreover the strength of structural member basically depends on the geometrical and physical property of the structural sections used. The quality control and production process prevailed in a particular country is also an important consideration and due to this reason the factors may changes accordingly for material with a statistically inferred characteristic value. It is true that LSD is a probabilistic approach of design method but in a codified form it becomes a semi-probabilistic method based on PSF format as in IS: 800-2007. So it is not mandatory for any structural engineer to go through a statistical calculation for practical design based on the code if not specially required for. Only the conceptual changes from the erstwhile deterministic thinking shall be philosophically understood by the engineers.

IV. A REVIEW OF TENSION MEMBER DESIGN CONCEPT BY LSD & WSD (BOTH 2007&1984)

To elaborate the concept of LSD a typical eccentrically connected single angle section is considered for study based on IS 800-2007. WSD of IS 800-2007 and IS 800-1984 also studied for safety, economy and conceptual comparison with LSD method. It shall be mentioned that in IS 800-2007 a brief chapter has been introduced as WSD. However this method of WSD is completely different from the traditional WSD (IS-800-1984). This WSD is based on the same concept of LSD but with permissible stress and un-factored load format. Major emphasis has been given by LSD codes in tension member design. Tension member generally regarded as the Fracture Critical Member (FCM) especially in bridge structure. FCM defines as "*steel tension members or steel tension components of members whose failure would be expected to result in a partial or full collapse of the bridge.*" [26] So the basic advancement of concept of design of tension member in LSD format shall be studied for successful implementation of it in practical design. In traditional WSD method of tension member design, the variables controlling the connection in tension member design were generally ignored and dealt with separately. In LSD method of design of single angle tension member govern by 4 distinct failure limit state.

a) Connection–
  i. Bolt/Weld -Shear & Tearing
  ii. Gusset Plate/Connecting Member-Yielding-Rupture.
b) Gross section Yielding of member.
c) Net Section Fracture & Shear Lag
d) Block Shear rupture
  i. Gross area Shear plane yielding & Net Area Tension plane Rupture.
  ii. Gross area Tension plane yielding & Net Area Shear plane Rupture

Failure in WSD (1984) considered purely within elastic limit and mode of failure considered only on Net/gross section yielding within permissible limit. Calculation of design strength for single angle ISA100X100X10 with safe bolted-gusseted connection is presented in Fig. 2. It shows that tensile capacity of ISA10010010 has got a upper bound value gross yielding strength T_{dg} (red line in Fig. 2) which govern at a longer connection length due to more numbers of lower grade bolt among four modes of failure. It is observed that smaller connection length (higher grade and less number of bolt) net section ruptured Tdn, block Shear tension Tbd1 & shear rupture Tbd2 shown in dotted line in Fig.-2, governs the design. This indicates the optimization for length of connection, angle size, gusset size, selection of bolt and pitch are required for efficient design of the member in tension.

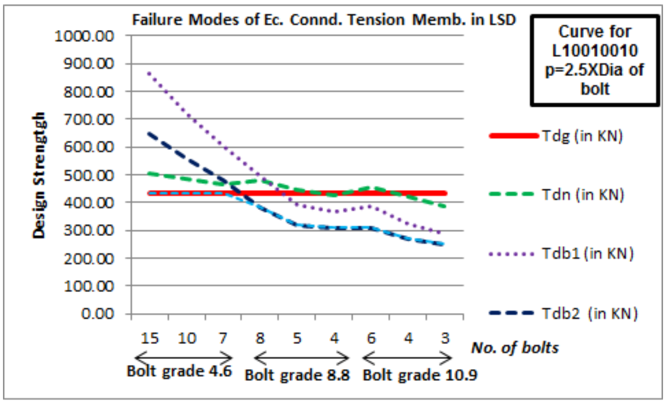
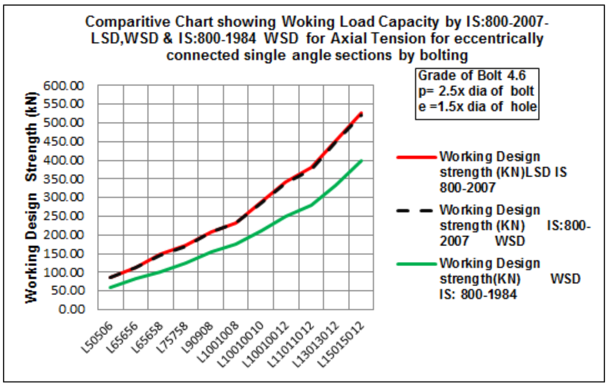


Fig. 2

From the calculation results' using IS 800-2007 LSD, WSD and WSD (IS 800-1984), the graphs in Fig. 3 & 4 are plotted for some eccentrically connected equal angle sections. This shows the design strength in 3-different methods of design by using grade of bolt 8.8 and 4.6. An interesting finding can be made from the Fig. 3, that the working design strength derived for LSD and WSD (IS:800-2007) are nearly same if connections are made with low strength 4.6 grade bolts. Higher grade of bolts (8.8) if used as in Fig. 4 WSD (2007) gives highest strength, even more than LSD for some sections (Load factor for LSD considered as 1.5). Reason for this is due to the increased connection length of WSD (2007) method in comparison to LSD. Connection length is larger because of the capacity of bolt as calculated by WSD (2007) is less (no. of bolt increased) than that of the LSD. Hence, the length of connection is increased in WSD (2007). In Fig. 3 say for L10010012 gives strength as 342.3 kN for LSD and 338.9 kN for WSD(2007) which is nearly equal .This shows using 4.6 grade bolt resulting larger connection length the failure mode governs as yielding of gross section in both the method. In Fig. 4 bolt requirement for LSD and WSD changes. For section L10010012 bolt requirement is 6 for LSD and 7 for WSD(2007) and length of connection 250 mm and 300 mm respectively. These shows that governing failure modes in WSD(2007) is yielding of gross section when length of connection is large. In contrary due to the lower length of connection for LSD Block shear rupture governs the failure mode and this produce lower design strength of LSD than WSD(2007). Moreover Fig. 3 and 4 show some higher design strength is available in LSD / WSD (2007) in comparison to WSD (1984). However, if the length of connection is reduced (rupture govern) by using higher grade bolt the design strength is nearer in all three methods when the angle leg thickness is less.

Fig. 3 shows design strength by WSD (1984) of the same sections is much less than LSD and WSD (2007) using bolt grade 4.6. In Fig. 4 it is observed there is no effect of connection on the design strength derived by WSD (1984) which is same as in Fig. 3. Design strength derived by LSD & WSD (2007) changes to reduced value, so, it shall be noted that the method for WSD given in IS: 800-2007 is totally different in all respect with traditional WSD (1984). WSD (2007) method of tension member is not a conservative design approach in respect to LSD or an alternative approach to traditional WSD.



Note : Strength of bolt is considered as per relevant codal stipulation

Fig. 3

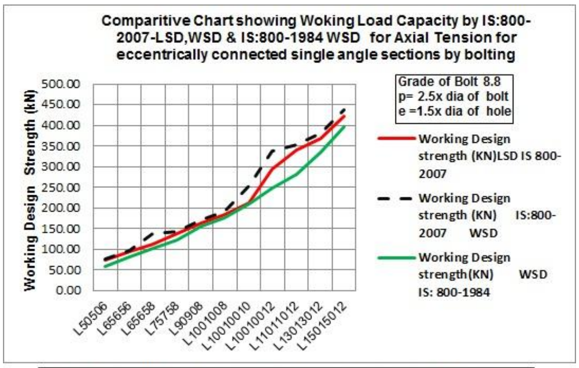


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Fig. 4

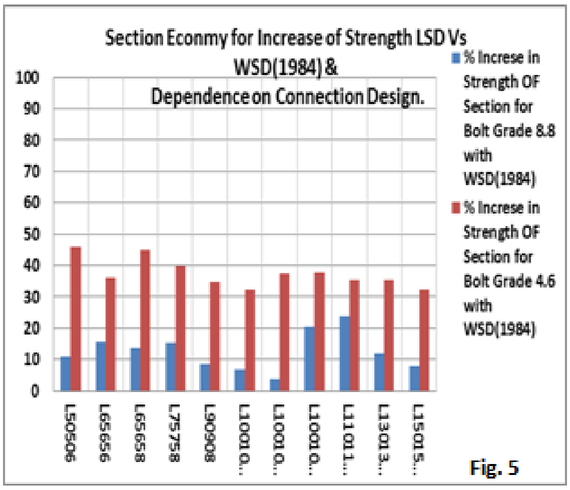

Fig. 5

In Fig.5 the bar graphs present the economy of section with LSD if modelled with different end connection in comparison to WSD (1984). It is observed that a connection using 4.6 grade bolt gives rise to higher length of connection resulting in more economic section than 8.8 grade bolts (small of length of connection) if used. It shall be noted that the economy of LSD with erstwhile WSD is not a straight forward issue and it can be achieved only by optimized design. Strength of the single equal angle sections differ from 10 to 30% if the strength of the bolt is reduced to 4.6 from 8.8 and consequent length of connection. It is observed from this design review that the length of connection finally govern the design. Here some length of connection, as calculated, is more than 15xdia of hole, shall be avoided for long connection inefficiency as stipulated in LSD codes. Economic size of the member is not only the issue for the whole structure. Due to longer length of connection size of gusset plate may also be large and hence the steel requirement for the whole structure may not be economic. **LSD method considered the economy of the structure in totality in contrast to the concept of individual member size economy as generally considered in tradition WSD**. This can be achieved by efficient optimization by LSD.

V.RISK ASSESSMENT LSD v/s WSD (IS:800-1984)

The table 2 shows that design strength (working load capacity) of single angle under tension by LSD becomes less in some case than the capacity derived from WSD. So the question arises if there is any underlying risk in the design by WSD (1984). Design strength by LSD method can be taken as more accurate for a given connection and a member as it is justified by statistical analysis of uncertain variable and reliability method by prediction of probable failure modes. Moreover, connection design is an independent and separate activity for design process of a tension member in WSD (1984). The member can only take the load if its connection is stable and safe as laid in LSD method. Connection design is a precondition of tension member design in LSD, which is ignored in traditional WSD method. In Table-2, it is shown that if ISA10010010 is connected with a gusset plate by 6-16 dia., 4-20 dia. and 3-24 dia. bolt the connection will fail by Block shear rupture. There is no check for this mode of failure in WSD (1984) and hence the risk of failure by rupture cannot be avoided. This shows that the safe design capacity derived from WSD shall require to be checked by LSD to avoid the early rupture failure of the tension member at connection end, before yielding.

Table-2: Comparative Chart of Working Design Strength of Eccentrically Connected Equal angles by LSD method IS: 800-2007 using Diff. grade bolts & IS-800-1984 Allowable Design Strength (WSD)

Trial section	Class of bolt	Dia of bolt(mm)	No. of bolt	Length of Connection Lc(mm)	Un-factored load (LSD) (kN)	Allowable Load (WSD) (KN)
L10010010	4.6	16	15	560	288.33	217.41
	4.6	20	10	450	288.33	209.84
	4.6	24	7	360	288.33	202.15
	8.8	16	8	280	256.04	217.41
	8.8	20	5	200	212.86	209.84
	8.8	24	4	180	206.04	202.15
	10.9	16	6	200	206.04	217.41
	10.9	20	4	150	181.05	209.84
	10.9	24	3	120	167.41	202.15

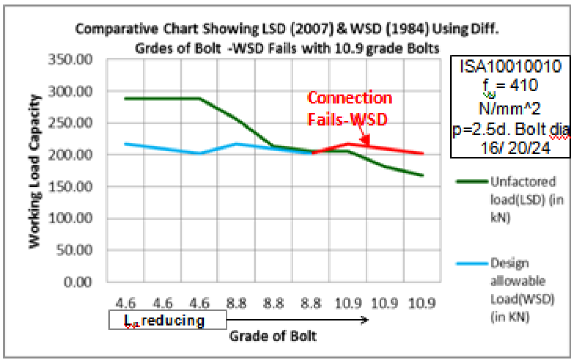

Fig. 6

In Fig. 6 it is shown that the red portion of the load capacity curve of WSD (1984) is unsafe due to early rupture of connection if length of connection is less with higher grade and less number of bolts.
All this above design calculation for table and chart by LSD, have been checked for actual bolt requirement and gusset size and thickness by gross yielding strength of the member.

VI. FINDINGS OF BOLTED CONNECTION OF ECCENTRICALLY CONNECTED SINGLE ANGLE

6.1 Static, Elastic, and inelastic stability of the connection in most cases govern the failure mode of a tension member and it is true for all other members under different forces, if designed by LSD. The upper bound capacity of gross yielding strength can only be achieved if the connection is suitably optimized with a specific member requirement.

6.2 In foregoing examples it is observed that block shear rupture failure governs in LSD method for single angle in many cases. Block shear failure occurs when high tensile force is to be resisted by higher grade bolt for short connection length where legs of the angle are thin.

6.3 In example above it is observed that the shear lag effect for outstanding element does not govern the design as the length of connection kept higher and deduction of area for single row of bolt is less. However residual stress and stress concentration factor in bolt area shall also be considered in a connection to transmit high tensile forces.

6.4 It is observed in Fig. 3 that if connection length is higher (4.6 grade bolts) then the LSD and WSD methods (2007) give same strength for most of the section. However, the length of section is small (8.8 grade of bolt), WSD (2007) gives higher strength of many sections even more than LSD. In practicing field a general notion always prevails that WSD gives conservative strength which is not true always for WSD (2007). And here the difference lies between traditional WSD and WSD (2007).

6.5 It is observed in the review that traditional WSD design is not always acceptable with any type of connection which can apparently transmit the forces. So major connection with high tensile forces shall always be checked by LSD or WSD (2007) if it is designed by traditional WSD (1984) method. Whereas WSD method of IS 800-2007 can be adopted, if opted by the designer, is safe as all the failure mode of LSD is included in this method.

Welded Tension Member

Welded tension member generally is not subjected to reduction of area from its gross area of the member. But net area has to be considered if there are holes for erection purpose to provide erection bolts. However the failure mode for the effective section shall be considered if there is chance for shear lag in outstanding (unconnected) element. Failure mode block shear also considered along the welding line.

However, Fig.7 shows that in general the gross yielding strength governs the design for welded connection. Fig. 8 shows the comparative chart for LSD and WSD which indicate a considerable economy of the section in LSD.

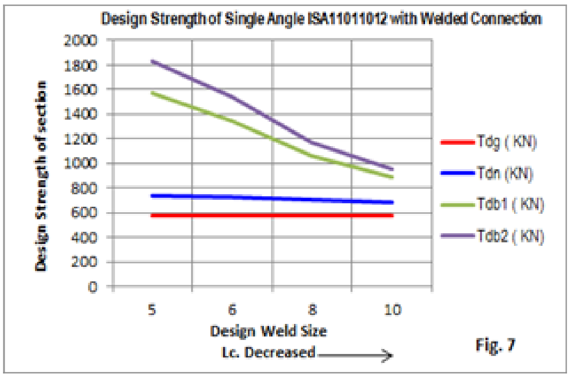

Fig. 7

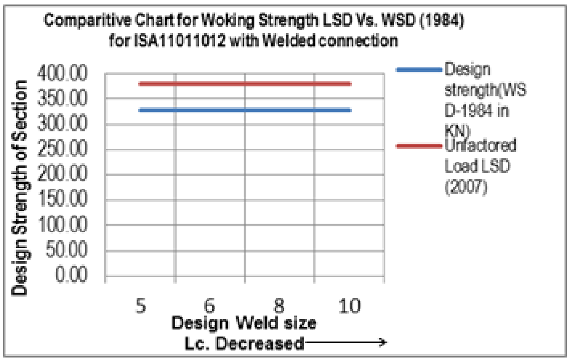

Fig. 8

VII. FINDINGS OF WELDED CONNECTION OF ECCENTRICALLY CONNECTED SINGLE ANGLE

7.1Unlike bolted connections, welded connection design by LSD method has distinct advantage to achieve cost effective section in comparison to WSD (1984) Fig. 8.

7.2 Due to no deduction of the gross area of the section the chances of block shear rupture mode of failure is very low as can be seen in Fig. 7.

7.3 Shear lag is there in outstanding element but due to gross area availability at connected leg, chance of rupture of section is low.

VIII. FINDINGS & DISCUSSION

From the above study of eccentrically connected tension members, the concept of LSD can well be established and following observations can be made.

8.1 Yielding of gross cross section of a tension member is always the upper bound or maximum capacity of the section.

8.2 Early failure may occur in connection zone before reaching the yield stress in the body of the member.

8.3 Connection governs the design in most of the cases, if not optimized to upper bound strength value through suitable iteration.

8.4 Load demand requires not only the member section capacity but the system in totality where its connection shall remain safe and stable.

8.5 Sections with bolted connections are more vulnerable to early rupture failure than the welded connection.

8.6 Design of Tension member has been made to rationalize by recognizing the actual sate of failure in inelastic regime.

8.7 Concept of sudden collapse of structure have been decreased by adopting higher factor of safety (γ_{m1} =1.25) with f_u with suitable reduction factor in comparison to safety factor at yield limit (γ_{m1} =1.1).

8.8 Economy of section is not a straight forward issue in LSD for bolted tension member that depends on efficient optimization of capacity and depends on the variable responsible for failure.

8.9 Safety aspect of structure system and its integrity are more emphasized in LSD method of design. In the tension member example it is observed that in LSD, only an isolated member is not designed but with its whole entity which includes its connection. This implies that LSD calls for the uniformity in risk reduction of the structure as a whole against any failure. So economy aspect of the LSD is implicitly addressed in a manner so that the uniformity of risk and safety level can be achieved for the structural system as a whole.

8.10 Traditional codified (1984) WSD method for a tension member in a structure might sometime lead to unsafe design through failure in connection. LSD check is required for safety of critical connection in structure.

8.11 WSD method given in IS: 800-2007 is producing same design result as in LSD at least for bolted tension member if section and connection are efficiently selected.

IX. CONCLUSION

9.1 It can be concluded that IS: 800-2007 is not a conventional revision of the 1984 code. Knowledge of reliability based concept, all over the world is advancing very fast. Traditional WSD as in 1984 (Not as in AISC 360-10) code has been completely rejected by all countries in the world. But in India practicing structural engineers are still facing some indecisiveness to implement this LSD concept through IS: 800-2007.

9.2 Implementation of IS 800-2007 by transition from traditional WSD is very important not only for the Indian practicing structural engineers but for effective utilization of steel in Indian construction industry. Consumption of structural steel in India (one tenth of China in 2013) [27] is alarmingly low though the advantage of using steel in comparison to other construction material is already established worldwide.

9.3 Implementation of large tall steel structures and long span steel bridges in India by indigenous design is still not frequent. Economy by LSD method for large steel structural system is already established in the world. This is only possible if our mind set of highly deterministic and elastic/linear methodology of traditional design can be changed to modern reliability based LSD method through effective up gradation of knowledge base.

9.4 For adoption of LSD in all levels more, more review and study of the codes and reliability base design approach is very important. Some important documents may be prepared and published for understanding of this LSD method (IS-800-2007) and its application as under

9.4.1 Limit state Design manual based on IS-800-2007 with commentary on code and worked out examples.(like AISC LRFD manual)

9.4.2 Basic Design requirement for LSD method for conceptual understanding of this new format. (like EN 1990)

9.4.3 Code calibration procedure of partial safety factor used in code, with sufficient statistical data for understanding of the codified safety format.

9.4.4 Authentication of available commercial software which included IS 800-2007 to avoid abuse of LSD and codes.

9.4.5 More clarity require for IS 800-2007 may be achieved by more documentation. For example, Shear lag criteria shall be implicitly included for all members (not only single angle) with clear sketches in tension member design and statistical validation of imperfection factor in Compression member design and so on like second order effect on beam column design.

9.4.6 Quality control shall be addressed and included in code or manual with more emphasis or otherwise more suitable reference may be made with codes like IS:1852-1985 (Reaffirmed 1995), IS:7215: 1974 with their revised publication.

9.5 Statistical inference shall be made on the prevailing practice in the country BIS, Insdag, IITs and other institution and individual has been contributing on this issue which may be very useful for the practicing engineers, but the situation demands more documentation on the subject, not only through academic focus but also by the practical applicability of LSD.

9.6 In this paper a review of only tension member based on IS 800-2007 is presented but all and every part of this code containing other structural members shall be studied and documented for more acceptability of this codified method and success of this big challenge faced by us in India today.

9.7 Finally it shall be acknowledged that the Indian construction industry is rapidly advancing with modern methods and equipment. Moreover first computerization of design by providing computer to the desk of every structural engineer in India is a great advantage for quality improvement of design work. This is a highly favorable condition for more integrated implementation of higher form of design and engineering through conceptual of reliability based limit state method.

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