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**Safety Concepts, with particular emphasis on Steel**

Les concepts de sécurité pour la construction métallique

Sicherheitsbetrachtungen mit besonderer Berücksichtigung des Stahles

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## INTRODUCTION

In the preceding paper Dr. Rowe has presented an excellent account of present day concepts used in design to insure adequate safety of structures. Emphasis was placed on the Limit State approach and its application to the design of reinforced and prestressed concrete structures. This paper is an extension of Dr. Rowe's and in particular deals with the application of safety concepts to the design of steel structures.

## DESIGN GOALS

Engineering design has been defined [1] as a purposeful activity directed toward the goal of fulfilling human needs, particularly those which can be met by the technological factors of our culture. Every design activity that finally leads to a physical embodiment of the designers conception must perforce make some use of technological factors. One of the most significant design activities affecting the design of a structure deals with quantifying the vague concept of factor of safety.

The goal of the structural designer is to provide a structure that will not only be safe but will perform in a manner suitable for its intended use over a given finite period of time. Failure to meet the goal for a steel structure is usually caused by structural inadequacy, fire, corrosion, extreme deflections or vibrations. Structural inadequacy, in terms of strength and deflection, can be avoided by providing ample maximum strength and stiffners to resist the expected static and dynamic loads, fracture and instability.

## DESIGN CONSIDERATIONS

To adequately design a structure requires repeated iterations to obtain the optimum configuration and size of elements using as a measure the structures intended use, least cost, aesthetics or a combination of these factors. Among the considerations entering into the design process are:

1. Selection of materials and the variation of their properties.
2. Selection of design static and dynamic loads and the variation of the loads expected during the life of the structure.
3. Determining the design life of the structure which is influenced by whether it is to be a permanent or only a temporary structure.
4. Expected quality of workmanship during construction.
5. Expected maintenance and inspection during the life of the structure. This latter item is quite important for a structure subjected to dynamic loads. Visual field inspection is not enough to detect flaws or possible fracture zones in the structure. More sophisticated methods are needed if we are to guard against failure such as the catastrophic bridge failure at Point Pleasant in West Virginia.[2] A few more failures of this type in a short period of time could result in a public demand that no structure be designed that could collapse due to the failure of only one member.

## CHARACTERISTIC STRENGTH

The single, most important structural property of a mild steel is its yield point.[3] This applies to both allowable stress design and plastic design. Winter[3] has reported on 3,974 mill tests of ASTM A-7 steel. For this steel the specified yield point is 33 ksi. He reported that the median mill test value was 38.7 ksi with a mean value of 40 ksi, and that less than 2% of the mill tests failed to meet the 33 ksi requirement. Another important steel property, required for the investigation of inelastic buckling of steel members, is the strain-hardening modulus and its variation. There is a great deal of statistical data on material properties available and Dr. Rowe in his paper has indicated that this data can be used to calculate the characteristic strength $\sigma_k$ by use of the equation:

$$\sigma_k = \sigma_m - k s$$

where $\sigma_m$ = arithmetic mean of test results

$s$ = standard deviation

$k$ = coefficient depending on probability accepted a priori, of obtaining results less than $\sigma_k$.

## CHARACTERISTIC LOADS

If statistical data on loadings is available than it is possible to use a similar equation to obtain the characteristic loading. However, little information is available on the variability of loading. In the United States there is a project underway to actually measure the live loads that are present in a large number of buildings throughout the country. For highway bridges variations in the live loads are caused by mixture of trucks and cars, new types of vehicles proposed for the future and the sometimes arbitrary raising of the legal load limits.[4] Wind loads, earthquakes, blast loads, temperature effects, ice load and stream flow add to the complexity of establishing characteristic loadings and their variations.

## ALLOWABLE STRESS DESIGN

Design of steel structures has traditionally been governed by allowable stress design. This method requires designing with given loads and an allowable stress taken as a fraction of the yield point stress. With this method it is practically impossible to estimate the actual factor of safety since the collapse load or the possible variation of the design loads is not known. In addition, the method neglects taking into account the full range of load-deformation behavior. Allowable stress design is slowly being replaced by a Maximum Load (Strength) design method.

## MAXIMUM STRENGTH DESIGN

Maximum load design of steel structures requires that members be so selected that they reach their maximum strength at a load which is calculated as the product of the characteristic load and a load factor.[5] This method of design is also referred to as Load Factor design. This design approach is semi-probabilistic in that statistical data is used when available to establish appropriate values of the load factors but it is still necessary to draw on past experience to a great degree in establishing some of the load factors. For the forseeable future it is apparant that not enough information will be available to allow the full probabilistic approach developed by Freundenthal[6] to be used in everyday design practices.

## MAXIMUM STRENGTH VS. LIMIT STATE

Dr. Rowe in his paper has throughly covered the Limit State method for concrete structures. A steel structure that has failed is said to have reached a limit state.[7] There are many such states, the most important being load limit, fatigue limit, stability limit and deflection limit.

It is appropriate to examine and compare how the safety concepts are developed for the two approaches, namely, the Load Factor design method and the Limit State design method.

The "Tentative Criteria for Load Factor Design of Steel Highway Bridges"(8) proposed for bridges in the United States specifies the following as the load factors to be used:

$$U = 1.25 \left(D + \frac{5}{3} (L+I)\right)$$

where
$D$ = Dead Load
$L$ = Live Load
$I$ = Impact
$U$ = Maximum Strength

In general: $\Phi \times U = \lambda \left( \alpha D + \beta (L+I) \right)$

where $\Phi$ = factor to allow for uncertainties in the magnitude of characteristic strength due to variations of material properties in the actual structure from that found in test specimens, corrosion, errors in the dimensions of the cross-section and other similar items.

$\lambda$ = factor to allow for overall effects, such as errors in design assumptions.

$\alpha$ = factor to allow for increases in the dead load of the structure arising either through calculation error or future increases in dead load.

$\beta$ = factor to allow for overloads.

In the Limit State approach each item is treated separately and partial factors of safety assigned. The partial safety factor for material strength is expressed by the relationship:

$$\sigma^{*} = \frac{\sigma_{K}}{\gamma_{m}}$$

where $\sigma^{*}$ = Maximum Strength U

$\sigma^{K}$ = Characteristic Strength

$\gamma_{m}$ = Partial Safety Factor

The partial safety factor for loads is expressed by the relationship:

$$S^{*} = \gamma_{S} S_{K}$$

where $S^{*}$ = Maximum design load

$S_{K}$ = Characteristic Load

$\gamma_{S}$ = Partial Safety Factor

By comparison it is evident that:

$$\gamma_m = 1/\Phi$$

$$\gamma_s^{D} = \lambda\alpha$$

$$\gamma_s^{L} = \lambda\beta$$

where $\gamma_s^{D}$ and $\gamma_s^{L}$ are the partial factors of safety for dead load and live load respectively. These partial factors of safety are used to reduce the characteristic loads due to overloads, errors in design assumptions and construction errors. They also include the coefficient $\gamma_c$ referred to by Dr. Rowe as taking into account the type of structure and seriousness of failure of the element of the structure under consideration.

If a value of $\gamma_m = 1.10$ is taken as a reasonable value for a steel structure then for bridges:

$$\gamma_s^{D} = 1.25 \times 1.0 \div 1.10 = 1.14$$

$$\gamma_s^{L} = 1.25 \times 1.67 + 1.10 = 1.90$$

The overall safety factor is the product of $\gamma_m$ and $\gamma_s$ and is tabulated for various stringer bridges in the following table:

| Span | R | $\gamma_m$ | $\gamma_s^{A}$ | $\gamma_m \gamma_s^{A}$ |
|---|---|---|---|---|
| 36' | 0.5 | 1.10 | 1.65 | 1.82 |
| 70' | 1.0 | 1.10 | 1.52 | 1.67 |
| 110' | 1.5 | 1.10 | 1.45 | 1.60 |

where R is the ratio of D to L+I

$\gamma_s^{A}$ is the average value of $\gamma_s$ for D+L+I

The criteria for steel bridges was set so as to provide the same section as provided in allowable stress design on the short span range of 30 to 40 feet and lighter sections for longer spans. The ratio of the yield point stress (36 ksi) to allowable stress (20 ksi) for ASTM-A36 steel is 1.80. An examination of the above table shows that for a steel span of 36 feet the factor of safety is 1.82 and reduces as the span length increases.

## CONCLUSIONS

There does not appear to be much difference, if any, between the Load Factor or Limit State approaches. There is a significant difference however in the philosophy behind each approach. Limit State is a much more logical and scientific approach to the problem of applying the concept of safety factor. It enables the designer to evaluate separately each item comprising the overall factor of safety and allows him latitude and guidance for setting values for unusual structures.

It seems apparent that concrete design is tending towards using the Limit State concept and it is logical that steel design should likewise be governed by the same concepts. Some of the partial safety factors for the Limit State approach would be the same for both materials. It would serve no useful purpose for steel design to be governed by Load Factors and concrete design by Limit State concepts.

Future research needs to be oriented toward supplying the necessary information to allow further refinements in the setting of the partial factors of safety. The structural behavior of three dimensional framework and three dimensional states of stress should be investigated. Further items needing more clarification are the variation of loads, and the limit states governing deflections, vibrations, wind, fatigue and fracture. The Limit State approach provides a usable everyday design procedures but its success will depend on obtaining the necessary information to assign proper values to the various partial factors of safety.

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SUMMARY

The paper by Dr. Rowe is extended to include a treatment of safety concepts applicable to steel structures. Design and considerations are discussed relative to structural failure, material properties and loadings. The Load Factor approach for steel design is developed and a comparison made between this approach and the Limit State approach. The conclusion reached is that the Limit State approach could well be used for both steel and concrete design. Future research that will be required for the success of the method is commented upon.

RESUME

L'exposé du Dr. Rowe a été développé pour inclure une étude des concepts de sécurité appliqués aux structures métalliques. Le but et l'étude des projets sont examinés quant à la fatigue des structures, aux propriétés du matériau et à la charge. L'auteur a développé pour les constructions métalliques la méthode des charges pondérées et il a comparé cette méthode avec la théorie des états limites. La conclusion est qu'on peut utiliser la théorie des états limites aussi bien pour les constructions métalliques que pour le béton armé. De futures recherches sont nécessaires pour le succès de la méthode commentée ci-dessus.

ZUSAMMENFASSUNG

Der Aufsatz von Dr. Rowe ist erweitert worden, um eine Behandlung von Sicherheitsbegriffen bei Stahlkonstruktionen einzuschliessen. Ziel des Entwurfes und Ueberlegungen werden in bezug auf Bruch, Materialeigenschaften und Belastungen besprochen. Es ist ein Verfahren der gewogenen Lasten (Lastbeiwertverfahren) für den Stahlbau entwickelt und mit dem Traglastverfahren verglichen worden. Die Folgerung daraus ist, dass das Traglastverfahren sowohl im Stahl- als auch im Betonbau angewandt werden kann. Besprochen werden auch die erforderlichen künftigen Untersuchungen für den Erfolg dieser Methode.

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