

# Theme VII: Progress on tall buildings, progress in the design of plate- and box-girders in steel, progress on bridge loading

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## **VII**

**Progrès dans les maisons hautes \***

**Progrès dans le dimensionnement des poutres  
à âme pleine et en caisson, en acier**

**Progrès dans la charge des ponts**

**Fortschritte bei Hochhäusern \***

**Fortschritte in der Dimensionierung von stählernen  
Vollwand- und Kastenträgern**

**Fortschritte bei der Erfassung der Belastung von  
Brücken**

**Progress on Tall Buildings \***

**Progress in the Design of plate- and box-girders  
in Steel**

**Progress on Bridge Loading**

\* Unfortunately the report "Progress on Tall Buildings" was not delivered by the time the whole work was given to the printer.

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## VII

### Progress in the Design of Steel Plate- and Box Girders

Progrès dans le dimensionnement des poutres à âme pleine  
et en caisson en acier

Fortschritte in der Dimensionierung von Vollwand- und  
Kastenträger in Stahl

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#### 1. INTRODUCTION.

It is not the first time that the undersigned has the duty to report about progress in the design of plate and box girders in steel. He was invited to establish the General Report in this theme at the New-York 1968 Congress of IABSE [A7] and, in 1971, at the request of the late professor BEER, at that time chairman of Commission 2 (Steel) of IABSE, he organized in London, jointly with professors L.S. BEEDLE and K.C. ROCKEY, a Colloquium entitled :

*Design of plate and box girders for ultimate strength*

whose proceedings, published in July 1972 [C7], were favourably received by the members of IABSE. This important source of references will be mentioned in the references as : IABSE London 1971 Colloquium.

This field of research is still in a state of rapid evolution. One main reason is the big accidents which struck four large steel box girders during their erection ([B1] to [B9]). These accidents triggered an important research effort in the countries most concerned, namely Great Britain and the Federal Republic of Germany with some additional work in Australia, Belgium, Japan and other countries. In Great Britain, a Committee, called the Merrison Committee, was appointed by the government and published its conclusions [D4] in 1972, in a form usually called the Merrison rules. The research on the strength of box girder bridges continues very actively in Great Britain, with the central activity at Imperial College, London. This Institution has organised from July 6 to 9, in consponsorship with the Institution of Structural Engineers, the Royal Institution of Naval Architects and Constrado an International Conference on Steel Plated Structures. The 22 papers cited from this source will be abbreviated in the references as "ICSPS paper N° X".

In Western Germany, a special subcommittee called "Unterausschuss "Stabilität" and especially its Working Group "Plate Buckling" was set up. The author participates, as foreign member, with professor P. DUBAS, to the work of this Committee, while a series of experimental and theoretical researches are still under way in Darmstadt, Hannover, Karlsruhe, Braunschweig, Bochum and Berlin. Finally, the author has the responsibility to lead a subcommittee of Committee 8 (Stability) of the European Convention for Constructional Steel-



work (ECCS). This Work.Group (8/3) devoted to the study of buckling of plates has, up to now, concentrated his efforts on the most urgent problems, namely the design of plate and box girders. His work up to June 1976 was summarized into two State-of-Art Reports that have been included in the

*Manual on the Stability of Steel Structures*

which forms the Introductory Report of the Triple

*Colloquium on the Stability of Steel Structures,*

which will take place in Tokyo (9.9.1976), Liège (Belgium) (13 to 15.4.1977) and Washington (17 to 19 May 1977) under the Joint Sponsorship of IABSE, ECCS, USSRC and Japan Stability Research Committee.

I shall try, in 25 minutes, to present you a broad survey of these extremely complicated problems. My written report will be much more complete than my oral presentation. In a subject as fluid as this one, you could not hope that I shall come out with clear-cut design rules. I shall be happy if I can review thoroughly enough the recent research literature in the field concerned, stress the progress already obtained, and show the trend of the current research effort.

## 2. CRITICAL APPRAISAL OF THE LINEAR BUCKLING THEORY OF PLATES AND THE LESSONS TO BE DRAWN FROM THE ACCIDENTS TO BOX GIRDER BRIDGES.

The linear theory of buckling of plates is based on the following main assumptions :

- 1) the plate is initially perfectly flat ;
- 2) the transverse displacement  $w$  at buckling are so small ( $w/t \approx 0,2$ ) that membrane stresses in the median plate are negligible.

Both these assumptions are wrong but, nevertheless, the linear theory can provide useful results *provided the safety factor* is selected on the basis of the relevant experiments.

The main practical outcome of above theory for stiffened rectangular plate panels is represented by both books by professor KLÖPPEL and his collaborators [A1] [A2], in which the charts are restricted to simply supported plates reinforced by open section stiffeners. The author and his staff have generalized KLÖPPEL's mathematics for orthotropic plates reinforced by closed section stiffeners ([A4], [A9]) and verified that this type of stiffeners are vastly superior to open section ones [A5].

However, there is to-day a very large consensus that the linear buckling theory of plates is not an adequate support for the design of plate-and box girders ([A3], [A9]).

The New-York IABSE Congress of 1968, in his conclusions, already stated [A10] that "The linear theory of plate stability is not an adequate basis for design of struts and girders consisting of thin-walled sections".... "New carefully planned test series and computer simulation," including the post-buckling behavior (membrane action) of the sheet", are therefore strongly recommended".

This opinion is based on the basic philosophy of the design rules which has been prevailing these last years. The philosophy generally accepted in Europe, for concrete as well as for steel, is the semi-probabilistic theory of limit sta-

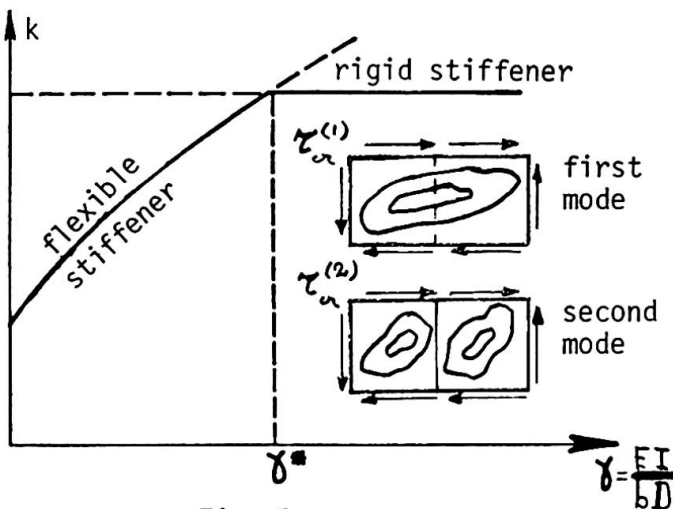
tes, in which the adequacy of any structure must be controlled in two limit states:

- a) the serviceability limit state (under working loads and other actions)
- b) the ultimate strength limit state (under factored loads and other actions).

Now, if the linear buckling theory predicts accurately the bifurcation buckling load of a perfect plane panel, it does not tell anything about the postbuckling strength of this panel. This is dangerous because this postbuckling strength depends very much of the rigidity of the frame surrounding the plate and still more on the type of stressing (shear, bending or compression). Therefore, low safety factors derived from the shear case where it is known since the WAGNER studies [C2] that the strength reserve can be enormous, may be-and have been - misleading if they are applied to compressed panels.

There is another, even more dangerous defect of the linear buckling, which pertains to the concept of optimum relative rigidity (Mindeststeifigkeit)  $\gamma^*$  of the non-dimensional factor  $\gamma = EI/bD$  (where  $EI$  is the flexural rigidity of the stiffener and  $D = Et^3/12(1 - \nu^2)$  the rigidity of the plate). The linear

theory predicts that such a stiffener has fifty chances on hundred to remain flat under the critical load (say  $\tau_{cr}$ , fig. 1), and thus to enforce the second buckling mode (Mindeststeifigkeit erster Art) or, at least, a mode where the stiffener remains *almost* flat (Mindeststeifigkeit zweiter Art). As, theoretically, there is no benefit to increase  $\gamma$  beyond  $\gamma^*$  this notion has been extensively used ([A1], [A2], [A4]) to design stiffened plated structures. However, this concept has nothing to do with postbuckling strength. 22 years ago, the writer demonstrated experimentally [A3] that  $\gamma^*$  stiffeners invariably bent in the postbuckling



- Fig. 1 -

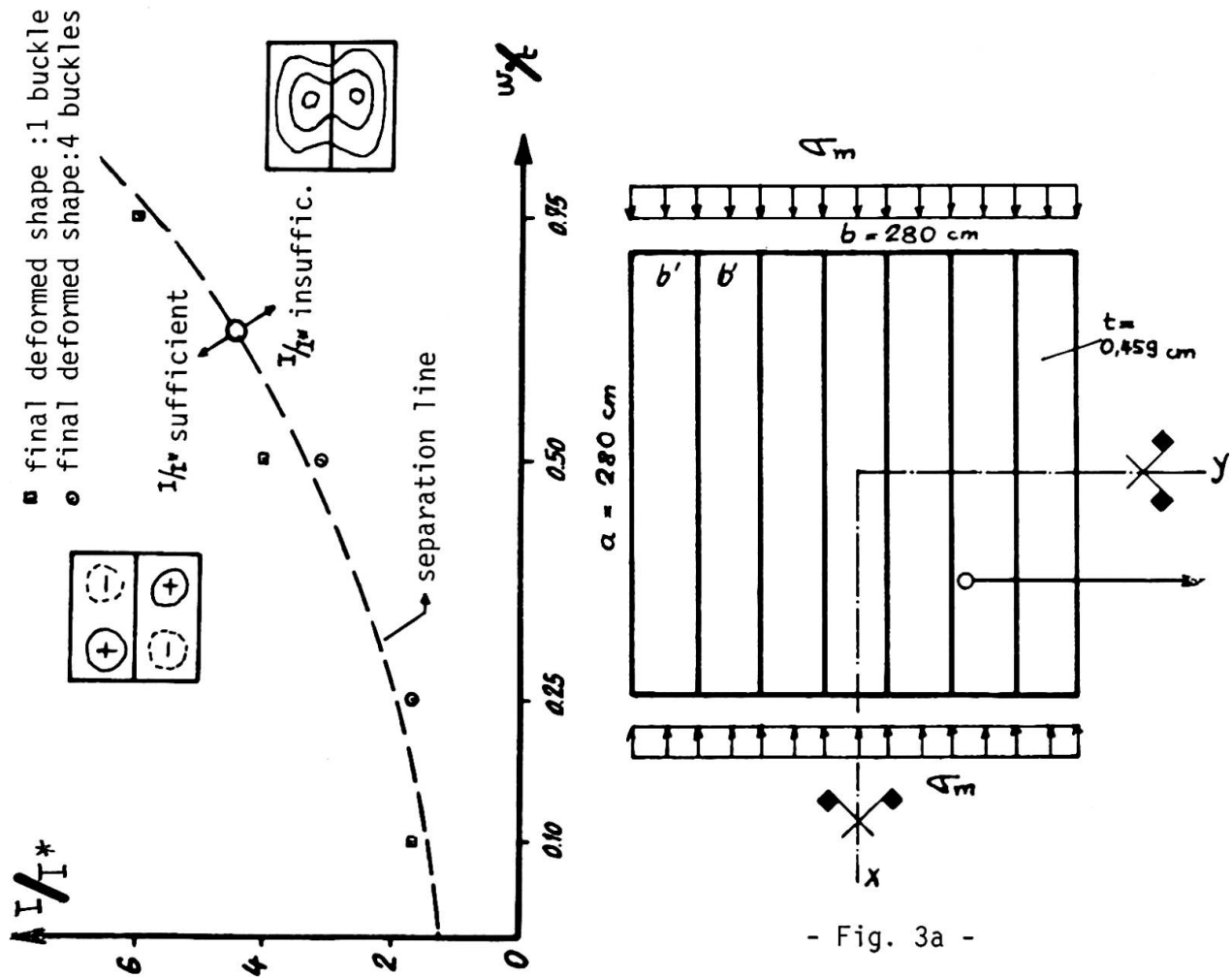
range if not sooner and recommended to multiply the theoretical value  $\gamma^*$  by a coefficient  $m$  equal to 3 to 7 according to the position of the longitudinal stiffener, in order to obtain a stiffener quasi-straight up to collapse. He insisted that an increase of about 4 on  $\gamma$  meant roughly an increase of 2 on the cross section area, and that the additional expense was very small, because the price of stiffener depends very much more on fabrication, adjustment and welding than on its weight.

Professor P. DUBAS was the first to show, by experimenting on stiffened box girder models [D1], that the  $\gamma^*$  concept was especially dangerous in the case of compression panels reinforced by many stiffeners. The same result had been obtained theoretically by SKALoud and NOVOTNY [A6] in the case of one or two stiffeners. Very recently, a collaborator of P. DUBAS, B. ROUVE, has obtained more striking results by using [A13] a large displacement finite element technique (see figures 2 and 3).

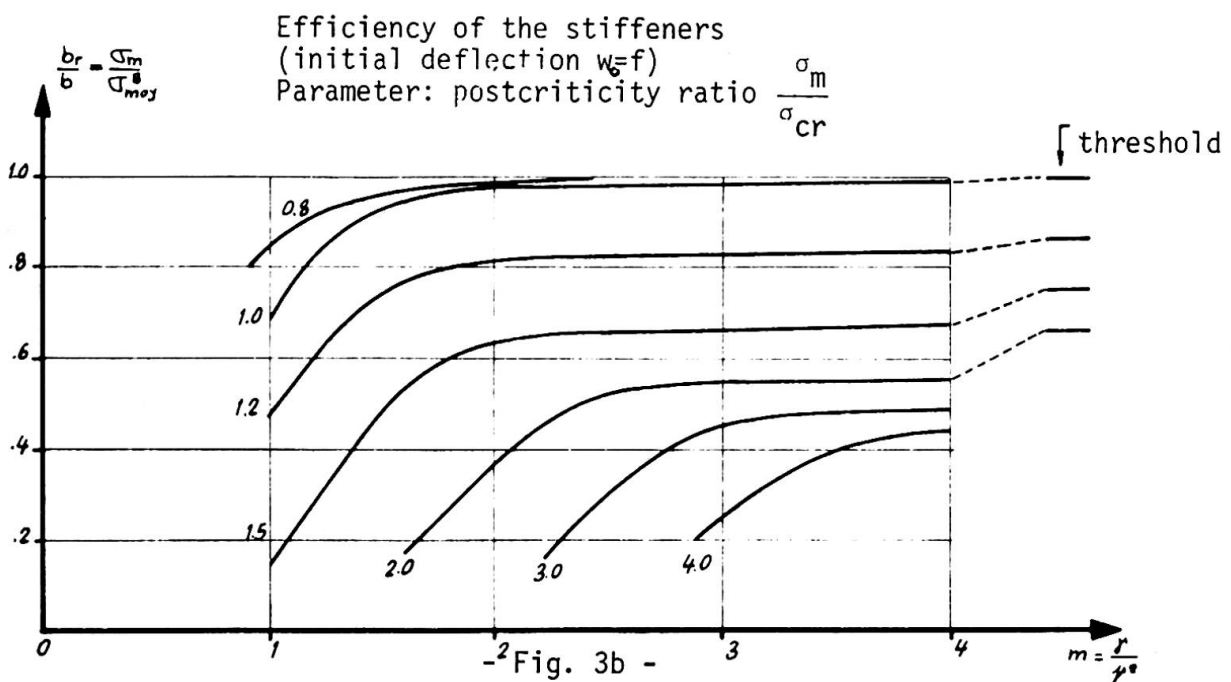
It begins to be possible, now, to derive the coefficient  $m$  arising in the relation

$$\gamma = m \gamma^*$$

*theoretically*, as a function of the extent of the postbuckling domain in which the stiffeners are requested to remain quasi-straight, as well as of the initial imperfection of the panel considered.



- Fig. 2 -



This shows, in passing, the importance of a good quality of fabrication or, in other words, of close tolerances, not only on the geometrical imperfections, but also on the structural imperfections represented by the residual stresses. While some measurements on real structures have already been made [B10] and tolerances are given in many national specifications (e.g. [D.14]) no agreement could still be reached at the ECCS level within the subcommittee 8/3 (plate buckling) of ECCS. It is clear that tolerances very exacting and difficult to control, such as those proposed in the Merrison Rules [D4] can have a very deleterious effect on the price of fabrication and therefore hamper very much the development of steel bridges.

This is the more true because these rules impose the complete recording, in the factory, of the fabrication phase and a lot of corresponding measurements.

It is now generally acknowledged ([B3],[B6],[B7],[B8],[B9]) that the accidents that occurred under erection on four big box girders were due partly to poor detailing [B3], and partly to inadequately low safety factors [D1][D2],[B7]. Specialists differ about the relative importance of these two reasons. Personally, I would say that, roughly, each of them bears half of the responsibility for the collapse.

It becomes clear, now, that the Merrison Rules, which had to be written in emergency conditions, are presently superseded; when they were published, they did represent a remarkable progress in many fields (shear lag, diaphragms, etc.). The engineering world was awaiting since two years the publication of a book that would explain clearly their scientific background. It seems, now, that this book will never appear.

It was clear, at the Conference held in July 1976 at Imperial College, London, that, due to the severity of these Rules, that are still in force in waiting for a new British code on steel bridges (the future BS 116 !), a very wide gap separates presently the fabricators and the research men who influence the design rules.

In the mind of present reporter, this is due to two very distinct reasons:

- a) due to the advent of the limit state philosophy and therefore of the probabilistic interaction coefficients, the number of loading cases seems to increase to unacceptable limits. In London, Wex and Brown [D33] explained that, for a two-span continuous bridge, 1744 loading cases have in principle to be investigated. Even if more than 90 per cent of these cases may be immediately discarded on the basis of engineering judgment, it remains nevertheless that about ten different loading cases should normally be investigated ;
- b) due to the introduction of the concept of *ultimate* strength limit concept, which replaces the concept of *elastic* response under *working* load, the analysis becomes now frequently elasto-plastic or, at least, non linear.

The duration and the price of the study of a box girder bridge are soaring up in such a way that some fabricators claimed in London for a dictator who would obtain the powers to simplify sufficiently the design rules.

To the present reporter, it is clear that the price to be optimized is the integrated price, comprising the study, and that therefore the length and difficulty of this study must be kept within reasonable limits. It is equally clear that fabrication tolerances must be imposed, but they must be reasonable and simple to apply. The only way to reach this goal is to base them on extensive measurements on actual structures and to let fix them by a

commission composed, by equal parts, of research men, design specialists and fabrication and erection engineers, working hand in hand.

With these statements in mind, we shall now try to offer a general view of the present state of development of the ultimate design rules. It must be admitted that the research has been so intensive since 1970 that we are still in a very fluid state. The outcome of the studies undertaken in Western Germany is just beginning to appear and it seems that new-research will be launched in the U.S.A. under the sponsorship of the Subcommittee on Ultimate strength of box girders of the ASCE - AASHTO Task Committee on flexural members. Present report has therefore every chance to become obsolete in a foreseeable future.

We shall first discuss plate girders and then, box girders. After that, we shall review some interim conventional design rules still based on the linear buckling theory. This report will conclude with brief considerations regarding the diaphragms of box girders, effect of local loads and other special problems.

### 3. ULTIMATE STRENGTH DESIGN OF PLATE GIRDERS.

Ultimate strength models for computing the ultimate carrying capacity of a stiffened panel in shear (plus eventual shear and compression) do not consider the linear plate buckling load as a limiting load, but as a basic value. Therefore, the design methods based on this concept are valid for technical construction with initial imperfections.

These methods all assume that the ultimate capacity can be evaluated from a cooperation of three independent actions, i.e.:

shear field-tension field-frame mechanism.

All methods assume that at ultimate strength, the shear field contributes the  $\tau_{cr}$  stress of the linear theory, which this author feels to be a gratuitous assumption (see in this respect [C15]). Some authors neglect completely the effect of the frame mechanism. The equivalent stress, calculated from the shear and the tension field, cannot exceed (under the factored loads !) the yield stress of the web material. When the frame mechanism is considered, one must take account of stresses induced by the bending moment of the girder by means of the bending rigidity and plastic moment of the flanges.

The basic model for ultimate shear strength of a plate panel is that developed between 1959 and 1961 at Lehigh University by K. BASLER ([C3],[C4],[C5]) under the guidance of B. THÜRLIMANN. This semi-diagonal tension field had already been studied by H. WAGNER in 1920 in the case of extremely thin webs (pure diagonal tension field [C2]) and it can be considered that a rather good approach of this basic model above was already given by RODE in 1916 [C1].

The BASLER approach was criticized by several researchers ([C23],[C6],[C15]) on the ground of a computation error. This objection is not accepted by BASLER. Anyway, there are presently about ten different models for the ultimate strength of a plate panel subjected to shear with eventual additional bending ([C8],[C9],[C10],[C11],[C12],[C13],[C14],[C16],[C17],[C20],[C21],[C22]).

The corresponding theories, whose main characteristics are summarized in TABLE 1, are briefly described in the State of Art Report [C19] to which we are forced to refer, due to lack of space. These theories have various degrees of generality; the most general should be applicable to a plate panel

Aspects	Aarau	Cardiff	Göteborg	Karlsruhe	Lehigh	Osaka	Prague- Cardiff	Stockholm	Tokyo	Zürich
1 Clarity of the method	fair	very good	very good	very good	good	fair	very good	very good	good	very good
2 Simplified method, easy for users	no	yes	yes	yes	no	no	no	yes	no	yes
3 Computer needed	no	charts	no	no	yes/no	yes	no/yes <sup>(1)</sup>	no	no	no
4 Account taken of longitudinal stiffeners	yes	yes	no	yes <sup>(2)</sup>	yes/no <sup>(3)</sup>	no	yes	no	no	no
5 Applicable to hybrid girders	yes	yes	yes	yes	yes	no	yes	yes	yes	yes
6 Applicable to unsymmetrical girders	yes	yes	yes	yes	yes	yes	no	no	yes	yes
7 Applicable to composite girders	no	nothing said	nothing said	yes	nothing said	no	no	no	nothing said	nothing said
8 Details for calculation of bending capacity	yes	yes	yes	yes	yes	no	yes	yes	yes	yes
9 Consideration of normal forces	no	no	yes	yes	no	no	yes	yes	no	yes
10 Details about $\sigma_{cr}$ of compression flange	yes	men- tioned	no	men- tioned	yes	no	men- tioned	men- tioned	no	no
11 Pure shear	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
12 Normal stresses due to bending	yes	yes	yes	yes	yes	no	yes	yes	yes	yes
13 Combined shear and bending	yes	yes	yes	yes	yes	no	yes	yes	yes	yes
(1) for solving a cubic equation ; (2) in the serviceability state ; (3) computer method takes account of longitudinal stiffeners.										

TABLE 1 - Summary of the aspects of the design methods.



dissymmetrical (that is, with unequal steel flanges or with the flange replaced by a reinforced concrete deck), hybrid, reinforced by various transverse and longitudinal stiffeners and subjected simultaneously to internal resultants  $M$ ,  $N$ ,  $V$  (the  $N$  is important, e.g. for cable-stayed bridges). It can be safely said that none of the theories presently proposed does cover this whole field. On the other hand, because the problem is extremely complicated, these models are all based on different simplifying assumptions, so that someone has rightly remarked that there are as many models as members in the research committee. The author must mention, in addition, that, even if some theories are accompanied by simplifying charts obtained on computer and intended to design offices, it is difficult to avoid a "cooking recipe" type of presentation, with the corresponding danger of misunderstanding. At the last Colloquium of W.C. II of IABSE (Dresden, September 1975), the author has emphasized [A16] the danger that this type of rule may present for the profession. A clear physical insight of any design rules is absolutely necessary and it cannot be said, for example that the Merrison Rules [D4] are a model in this respect. Anyway, Working Group 8/3 of ECCS has undertaken the tedious task to calibrate the ten methods against *all* valid known tests. A similar calibration is contained in the American Guide about structural stability, edited by Bruce JOHNSTON [A19].

The origin of the tests used is indicated below, while TABLE 2 gives, for each method, the mean value "m" of the ratio of predicted to observed load as well as the corresponding standard deviation.

Test results from different sources have been used to calibrate the design methods. These tests have been classified into two different groups :

- (a) webs with transverse stiffeners only ;
- (b) webs with transverse and longitudinal stiffeners.

Only the tests satisfying the requirements proper to each method have been considered for the statistical calculations (TABLE 2).

The sources are as follows :

BASLER, YEN, MÜLLER and THÜRLIMANN  
 ROCKEY and SKALOU  
 LONGBOTTOM and HEYMAN  
 SAKAI, NISHINO and OKUMURA  
 EVANS, PORTER and ROCKEY  
 DIMITRI and OSTAPENKO  
 SCHUELLER and OSTAPENKO  
 SKALOU  
 D'APICE and COOPER  
 COOPER, LEW and YEN  
 KONISHI  
 FUJII  
 CARSKADDAN  
 STEINHARDT and SCHRÖTER

Method	Transverse stiffeners only			Transverse and longitudinal stiffeners		
	n	m	sd	n	m	sd
Aarau	42	0.99	0.20	48	1,01	0,21
Cardiff	44	1.02	0.06	66	1.00	0.07
Göteborg	33	0.99	0.12	-	-	-
Karlsruhe	78	0.97	0.14	102	0.96	0.14
Lehigh	48	1.02	0.12	60	1.02	0.11
Osaka	36	1.07	0.17	-	-	-
Prague-Cardiff	32	0.98	0.08	46	0.99	0.07
Stockholm	33	0.96	0.11	-	-	-
Tokyo	40	0.95	0.15	-	-	-
Zürich	30/26	0.79/1.06	0.25/0.18	-	-	-

TABLE 2 Calibration against test results.

n : number of tests compared with design method ;

m : mean value of ratio of predicted to observed load ;

sd: standard deviation.

It is seen that, if some simple methods are deliberately safe, all can be used with confidence at least in the case of static loading provided they are not applied to exceptional cases which would be completely outside the field of the tests.

#### 4. ULTIMATE STRENGTH DESIGN OF BOX GIRDERS.

While everybody agrees that there is a certain interaction between the webs and the compressed flange of a box girder, the complexity of the problem is such that, presently, all methods apply to isolated stiffened flanges subjected to a compression force either constant ( $V=0$ ) or variable along the span ( $V \neq 0$ ), plus eventually torsion ( $M_t \neq 0$ ).

A problem still unsolved is whether it is economically interesting to "expand" the cross section in order to increase the strength of the girder, even at the expense of a reduction of the collapse stress, or not. A study of this problem would be especially welcome.

While computation models applicable to panels reinforced by very stocky stiffeners and used e.g. in naval architecture are known for a long time (see e.g. the state of the question made in [D2]), non linear models taking account of the actual support conditions of the plate panel (roughly simple support on the four edges), of the orthotropic character of the orthogonally stiffened panel and the membrane restraining stresses have appeared only very recently. We shall therefore divide the following discussion in two parts.

##### 4.1. MODELS APPLICABLE TO STRONGLY STIFFENED PANELS, WHICH BUCKLE ALMOST CYLINDRICALLY.

After the YOSHIKI model [cf. D2], the ultimate strength of stiffened panels could be evaluated by the FAULKNER formula, [cf. D2], which, like the WINTER formula, is based on



the concept of effective width and which was derived from a series of full-size buckling tests of stiffened panels of warships.

This type of model is especially cultivated in Great-Britain, where it seems to be postulated that optimum design corresponds always to very stocky stiffening.

The models used for the design of stiffened plates were developed on the basis of several previous valuable studies of the non linear behaviour and ultimate strength of isolated panels, first in the elastic domain [D20], then in the elasto-plastic one, with account taken of an initial curvature and of residual stresses ([D6], [D7], [D21], [D22], [D25]).

The first of this models, presented in the Merrison rules [D4], was considerably criticized as being complicated and oversafe for what regards the serviceability criterion. The subsequent models tried to correct this main defect. They were developed by DWIGHT and LITTLE at Cambridge [D6], HORNE and NARAYANAN at Manchester [D8], WALKER and MURRAY at Melbourne [D7] and they have benefited from a considerable amount of tests, some of them on stiffened panels discarded from the original Lower Yarra bridge structure. Dr. DOWLING and his collaborators at Imperial College have developed a more general model [D31], which is said to be able to take account of postbuckling effects, but has not been tested in the field of flexible stiffeners up to now. The degree of agreement of all those models with the tests will be discussed further on.

#### 4.2. NON LINEAR MODELS APPLICABLE TO THE LARGE DEFORMATIONS OF RECTANGULAR PANELS SIMPLY SUPPORTED ALONG ALL FOUR EDGES.

Prof. DUBAS was the first to demonstrate experimentally [D3] that designs of compressed stiffened panels based on the  $\gamma^*$  star concept were highly dangerous and that the usual safety factor of 1.35, applicable to shear panels of plate girders, had to be considerably increased in the case of compression panels. MAQUOI, MASSONNET [A8] and SKALoud [C7] showed that this conclusion could be derived theoretically in the case of stiffened imperfect panels reinforced by a unique longitudinal stiffener and uniformly compressed.

The Zürich design method proposed by Prof. DUBAS [D38] derives directly from his tests and is a modification of the classical (linear) buckling approach to stiffened plates.

As a measure of the stiffened plate's capacity to carry load beyond the critical buckling stress, use is made of MASSONNET's coefficient

$$m = \frac{\gamma_{\text{post-cr}}}{\gamma_{\text{linear}}}$$

where  $\gamma = \frac{EI}{bD}$

is the well known relative rigidity of a stiffener.

DUBAS found by his tests that an empirical value of  $m = 4.5$  gave a good agreement with the theoretically predicted failure loads. To estimate the moment carrying capacity of a given stiffened box girder, he proposes that :

- 1) The effective rigidity of the stiffeners be divided by five ;
- 2) the value of  $\gamma$  so obtained should be used (using eventually the charts of [A1, 2] to calculate  $\sigma_{cr}$  ;

- 3) the effective breadth of flange be calculated using  $\sigma_{cr}$  and hence the elastic section properties as obtained ;
- 4) the maximum moment be obtained using these section properties and  $\sigma_{max} = \sigma_r$  (yield stress).

The first accurate evaluation of the postbuckling strength was obtained in 1971 by MAQUOI and MASSONNET's theory [D2], which was subsequently shown to be in good agreement with an important series of tests ([D5], [D9], [D10]).

The theory is based on a suitable generalization of the von KARMAN-MARGUERRE non linear equations of moderate deflections of plates to orthotropic, eccentrically stiffened plates. The main assumptions are

- a) The initial imperfection is a doubly sinusoidal buckle (fig. 4)
- b) The additional deflection is affine to the first buckling mode of the linear theory, which is also a doubly sinusoidal buckle.
- c) The boundary conditions of a plate panel situated between two successive nodal lines are those indicated in fig. 4.

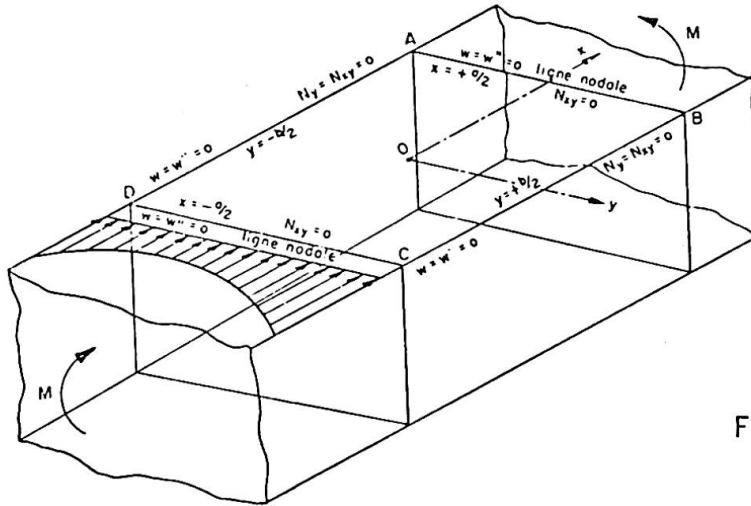
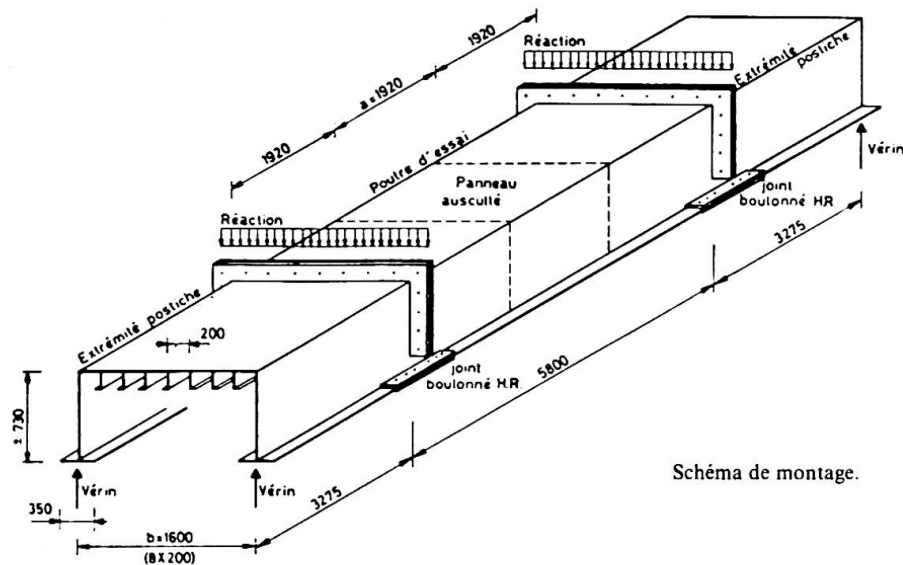


Figure 4

In the equations, the stiffeners are assumed to be "smeared" continuously on the compressed plate. The theory gives the efficiency  $\rho_g$  of such a "continuously stiffened plate". To take account of the discontinuous character of the stiffener, the effective width formula of FAULKNER is applied, which gives a local efficiency  $\rho_l$ . The total efficiency  $\rho_t$  is assumed to be the product of the two efficiencies  $\rho_g$  and  $\rho_l$  above.

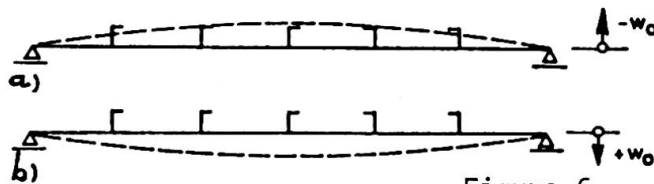
The ultimate strength is assumed to be reached (in agreement with the recommendations of WOLMIR [A19]) when the mean value of the membrane stresses along the unloaded edges AD or BC of the compressed panel, reach the yield point. A series of large size models [D10] (Fig. 5) have been executed which have shown that

- a) above criterion of collapse was accurate, but a little safe ;
- b) the theory was in good agreement with the tests.
- c) there was a considerable postbuckling strength reserve in the case of slender stiffeners.



- Figure 5 -

The Karlsruhe method developed more recently by STEINHARDT, VALTINAT and RUBIN, ([D17],[D18],[D32]) has several characteristics in common with the Liège method. However, it is more accurate, because it takes account of the discontinuous character of the stiffeners and leaves open the form of the transverse section of the buckle, which is determined so as to minimize the potential energy. It also distinguishes two types of collapse, by bending on the side of the stiffeners (fig. 6.a) and by bending on the side of the compressed plate (fig. 6.b).



-Figure 6 -

In addition, the thesis by Dr. RUBIN [D18] presents a series of charts that should facilitate considerably the practical use of the method.

A useful generalization of both non linear theories above has been presented in 1976 as Doktor Ingenieur Thesis by Dr. CHANG SUNG Pil [D19]. It is a non linear theory, based almost on the same assumptions as the Liège and Karlsruhe method. The ultimate strength N° 1 is the load for which the compression stress at the edge of the most stressed stiffener reaches the yield point. The ultimate strength N° 2 is that for which, in the middle plate of the plane, the equivalent stress reaches the yield stress.

The main progress of the thesis is to be applicable also to closed section profiles. For open section stiffeners, it becomes almost identical to the MAQUOI-MASSONNET theory.

Large closed section stiffeners are now used quite generally for the orthotropic bridge floors. In his paper to the London Conference, DUBAS [D34] demonstrated that they furnish also a convenient and economical solution for longitudinal web and plate stiffeners. Intersection problems with the transverse stiffeners can be avoided by placing each category of stiffener on a different side of the plate. In his discussion of DUBAS's paper, KLEMENT (Austria) recommended highly the closed section stiffeners. They are used in bridges in Austria since 20 to 30 years with no corrosion problems.

#### 4.3. CHARACTERISTICS OF THE VARIOUS METHODS.

The degree of generality of the various methods may be seen from TABLE 3 in which the available methods have been separated in the two categories corresponding to sections 4.1. and 4.2. above, respectively.

Aspects of Stiffened Compression Flange, Covered in the Different Methods	Method							
	Merrison Rules	Cambridge Method	Monash Method	Manchester Method	Imperial College	Zürich Method	Liège Method	Karlsruhe Method
1. Asymmetry of cross-section of flange about horizontal axis	✓	✓	✓	✓	✓	-	-	✓
2. Buckling of plate between stiffeners	✓	✓	✓	✓	✓	✓	✓	✓
3. Torsional buckling of stiffener outstand	✓	-	-	-	✓	-	-	-
4. In-plane transverse stresses in flange plate	✓	-	-	-	-	-	-	-
5. In-plane shear stresses in flange plate	✓	✓	-	-	✓	-	-	-
6. Locally applied lateral loading	✓	-	-	-	✓	-	-	-
7. Variation in axial load along length	✓	✓	-	-	✓	-	✓	-
8. Overall curvature of box girder	✓	-	-	-	✓	-	-	-
9. Overall postbuckling behaviour of flange	✓	-	-	-	? ✓	-	✓	✓
10. Welding residual stresses	✓	✓	-	✓	✓	-	-	-

TABLE 3

#### 4.4. AGREEMENT BETWEEN THEORY OF TESTS.

The five british and australian methods are in satisfactory agreement with the corresponding tests, in which the lateral edges were kept free. To this reporter, these are wide column tests rather than tests on actual stiffened com-

pressed flanges, which are obviously held laterally ( $w=0$ ) by the webs of the box girder.

For the details of the statistical comparison, which take two pages, the reader is referred to [D38].

We shall reproduce here only the TABLE 4, which gives the statistical comparison between the 8 design methods and 12 actual tests on complete box girders, undertaken partly in Liège and partly in London. It is seen that all methods are safe - with varying degrees of safety - and give decent standard deviations, the more dispersed being the Karlsruhe and Monash Methods.

#### 4.5. SHEAR LAG.

A problem that complicates the design of a box girder which is subjected to a bending moment  $M(x)$  variable along the span and accompanied therefore by the shear force  $V = dM/dx$  is that of shear lag. This expression designates the unequal distribution of the normal stresses over a cross section that is due to the (first order) in plane deformations of the component plates due to in-plane shear. This phenomenon was studied in the case of perfectly flat panels by ABDEL-SAYED [D13]. This problem was carefully studied at Imperial College by DOWLING and his collaborators, working for the Merrison Committee ([D11], [D12]) and simple approximations for design have been obtained. They are more refined than the rules given by the German specifications about steel bridges [D14] because they take account of the orthotropic character of the compressed flange, or, otherwise speaking, of the effect on shear lag of the longitudinal stiffeners.

In the postbuckling range, there is another type of shear lag; MAQUOI and MASSONNET have shown ([D15], [D27]) that, when the two types of shear lag occur simultaneously, the net effect is less than the product of the two isolated effects. In other words, a safe value of the efficiency of the girder is obtained by multiplying the efficiency  $\rho_t$  as given by the MAQUOI-MASSONNET theory in the case of pure bending ( $V = 0$ ) by the efficiency factor  $\rho_0$  corresponding to the first-order shear lag of the perfectly flat panel.

In a very recent paper presented at the July 1976 London Conference, DOWLING, MOOLANI and FRIEZE, on the basis on three point-loaded box girder models [D28], show that, in the ultimate condition, shear lag has little weakening effect on flange strength, due to plastic redistribution, and may be completely ignored if :

- a) the stiffeners are stocky enough to sustain a strain equal to 2.5 the times yield strain without significantly unloading ;
- b) the plate panels are capable of being strained up to 4 times the yield strain without significantly unloading.

The shear lag effects are also being studied now in Germany [D30], but the researches are not enough advanced to produce definite conclusions.

The paper by LALLY and WOLCHUK [D29] gives interesting details about the American specifications for box girders bridges. It indicates that the design of plating in compression is based on an elastic-plastic buckling curve, which, like in Great-Britain, disregards any postbuckling effect.

Two still rather obscure problems are :

- a) the design of the stiffeners for sufficient ultimate strength [D35] and
- b) the behaviour of the compressed plate when (due to torsion and even shear-lag), it is subject to combined direct and shear in-plane loading [D36].

DESIGN METHOD		TEST RESULTS		TOTAL 12	N
		LIEGE 6 tests	IMPERIAL COLLEGE 6 tests		
ZURICH	n	6	6	12	5
	m	0.869	1.004	0.937	
	sd	0.089	0.052	0.099	
MERRISON	n	6	6	12	1
	m	0.702	0.844	0.773	
	sd	0.058	0.138	0.126	
LIEGE	n	6	6	12	0
	m	0.751	0.878	0.815	
	sd	0.108	0.076	0.113	
CAMBRIDGE	n	6	6	12	0
	m	0.704	0.804	0.754	
	sd	0.063	0.048	0.075	
KARLSRUHE	n	6	6	12	1
	m	0.817	0.915	0.866	
	sd	0.107	0.178	0.170	
MONASH	n	6	6	12	0
	m	0.693	0.762	0.729	
	sd	0.168	0.110	0.100	
MANCHESTER	n	6	6	12	0
	m	0.756	0.871	0.814	
	sd	0.096	0.088	0.108	
IMPERIAL COLLEGE	n	6	6	12	0
	m	0.693	0.758	0.726	
	sd	0.086	0.123	0.111	

n = N° of tests compared with design method

m = Mean value of ratio of predicted to observed load

sd = Standard deviation

N = N° of cases where ratio of predicted to observed load exceeds one.

TABLE 4 - Calibration against box girder tests.



## 5. DIAPHRAGMS.

Not so long ago, diaphragms of box girders were verified by very crude methods. Because of the collapse at Milford Haven, which is attributed to a diaphragm weakness [B5] and due to the capability of elastic or elastoplastic finite elements, including eventually large displacements, a lot of studies have been devoted to diaphragms in Great-Britain. The first results, applicable to thick unstiffened diaphragms, are given in the Merrison Rules [B1] and studied in detail in [E2]. More recent results on stiffened diaphragms of trapezoidal box girders have been published [E3] or presented in July 1976 at the London Conference ([E4] [E5]).

## 6. FABRICATION PROBLEMS.

The discussion at the London 1976 Conference have shown that it was absolutely necessary to establish a set of realistic fabrication tolerances that would be accepted together by the designers and fabricators. This would probably require an international cooperation.

We shall content ourselves, here, to mention the paper by HORNE and NARAYANAN [D24] in which the authors describe the effect on ultimate strength of welded stiffened panels loaded in longitudinal compression of various fabrication procedures (intermittent versus continuous plate/stiffener welds), various types of local imperfections, various procedures for restoring longitudinal straightness in panels which were bowed during fabrication. The perhaps most astonishing result pertains to the eccentric longitudinal stiffener splices on flat stiffeners, which had been heavily blamed after the Melbourne disaster (see [B6] to [B9]).

According to [D24], these eccentric splices should be equivalent to concentric splices for what regards ultimate strength, provided a continuous connection exists between stiffener and plate.

## 7. OTHER PROBLEMS OF PLATE GIRDERS : PLATE GIRDERS WITHOUT STIFFENERS, EFFECTS OF CONCENTRATED LOADS, HYBRID GIRDERS, SPECIAL PROBLEMS.

There are a lot of special problems concerning plate and box girders which should be now discussed. The first of them concerns the effect of more or less concentrated transverse loads applied to the compression flange and acting on the girder in combination with the general resultants M, V, N. This problem seems to-day almost clarified, due to the efforts of ROCKEY [C7] [F4] and BERGFELT [F5]. The swedish school of research has also proposed, since about 15 years, a set of rules for the design of plate girders of moderate size, used in buildings, and subject to distributed static loads. These girders have no stiffeners, except at the supports. The main progresses in this field have been obtained by GRANHOLM, BERGFELT [F1] and HÖGLUND [F2]. HÖGLUND has also given rules [F3] to take account of the presence of holes in the web. The swedish rules are based on the postbuckling resistance of the thin web. Commission 11 of ECCS, under the chairmanship of Prof. REINITZHUBER, has actively studied the problem and ECCS Recommendations for the design of this type of girder will be published very soon.

At the London Conference of July 1976, van DOUWEN has demonstrated [F6] the technical and commercial advantages of this type of girders, which enable the fabricator to reduce considerably his investment in plates compared to the considerable stock which must be maintained in the case of rolled profiles.

## 8. THE PRO- AND AGAINST ULTIMATE STRENGTH DESIGN RULES FOR PLATE AND BOX GIRDERS.

While ultimate strength design rules are in principle vastly superior to the conventional rules based on the linear theory of buckling, there are numerous objections against them, which eventually carry a lot of weight.

### 8.1.

In principle, - as was emphasized in the London discussions at ICSPS by professor STEINHARDT, structures subject to moving loads should be designed elastically (even if advantage is taken of non linear membrane effects) and real plastic design should be reserved to compact sections, in the AISC Specifications meaning of this word. The author has always defended this point of view; indeed, not to speak of the fatigue problems, there seems to be a blunt contradiction between designing sections for ultimate strength and still continuing to determine the M,N,V diagrams on continuous girders by using elastic theory; the fact that a similar situation exists in reinforced and prestressed structures is not sufficient to justify it.

### 8.2.

Above limitation of ultimate strength methods to bridges can be obtained automatically if proper control is made of the serviceability limit state. We think, here, of the "breathing" of webs, which can produce fatigue cracks in the heat-affected zones near the flanges and/or transverse stiffeners ([A11], [A12]).

It seems that our tchecoslovakian colleagues have similar ideas, because the paper by DJUBEK and SKALOUD [C18] about the new tchecoslovakian standard for plate girders distinguishes carefully between fixed and moving loads. In the case of moving loads, non linear elastic rules, due to DJUBEK, are proposed, while plastic mechanisms (ROCKEY-SKALOUD) are reserved for the case of fixed loads. According to DJUBEK, Professor BROUDE has developed similar rules in USSR for the design under moving loads.

The ultimate concession regarding plastic action that could be made to ultimate strength methods would be to take as ultimate load the shake-down load (in the sense of this expression in plastic theory) and not the collapse load. Unfortunately, this would still complicate further the design rules.

### 8.3.

The elasto-plastic phenomena at collapse being extremely intricate, the ultimate strength methods are forced to rely on simplified models and assumptions. While at least some of these models are conceptually simple, the design rules take easily the shape of "cooking recipes", that the designer does not understand, what the present author considers to be productive of misunderstanding and therefore highly dangerous for the profession, not to



speak of the unpleasantness of the teaching [A16].

#### 8.4.

The ultimate strength methods cannot be general. New technical developments about cable-stayed bridges, (biaxial compression plus shear in the foot of the towers, etc) offshore structures, etc... are continuously bringing about new problems that must be solved without waiting until the proper corresponding ultimate strength model is developed.

#### 8.5.

For all these reasons, that have been analyzed a little differently by SCHEER and NÖLKE [A18] at the London Conference on Plated Structures, there is a need for interim design rules, still based on the linear buckling theory, because the designers need them to build.

These rules [A16] have been developed in cooperation between the german Working Group "Plate Buckling" of the german "Unterausschuss für Stabilität" and the Working Group 8/3 of ECCS, and particularly Prof. DUBAS, Dr. MAQUOI and the author. They have appeared as an Appendix to the ECCS Recommendations for the Design of Steel Structures and are justified scientifically in the Manual on Structural Stability [A15].

For the detailing problems (welded or bolted connections of plates and stiffeners), above rules give detailed prescriptions which should prevent the return of collapses during erection.

The safety has been adjusted by the introduction of correction factors so as to take account of the varying amount of postbuckling strength with the type of loading of the panel (shear or compression) as demonstrated by the tests. While it is openly admitted that this "manipulation" of the safety factors is not a very scientific procedure and that the safety should rather be a result of the basic principles of the design theory, it is felt that the resulting rules have the considerable advantage of being both simple and safe. The author believes therefore that, in spite of their title "provisional rules", they will still be applied for a long time.

### 9. RECOMMENDATIONS AND CONCLUSIONS.

#### 9.1.

An extremely large research effort has been made these last six years towards a better understanding of the ultimate carrying capacity of plate and box girders, but it remains to digest the corresponding research papers in order to transform them into acceptable design rules.

#### 9.2.

Quite apart from the particular problem of plate and box girders, the semi-probabilistic theory of limit states should be carefully weighted in order to maintain the computational effort of the designer within a decent percentage of the total price of the structure. For this to be obtained, methods should be found to identify the few limit states that are really governing.

## 9.3.

The Merrison Rules were interim rules, written in a period of emergency. They have performed their main duty, which was to protect against new accidents. The research launched by the Merrison Committee has brought a wealth of new scientific information.

## 9.4.

The Merrison Rules must now be replaced, as soon as possible, by more simple specifications, because they are hampering the development of long span steel bridges. The truth is somewhat in the middle between the Merrison Rules and the dangerous oversimplified rules that some designers would favour at any cost. It will, however, be difficult to obtain these desirable balanced rules by Committee work, because research men and fabricators have widely different views. Perhaps will it be necessary to appoint a kind of wise and competent "dictator" to "distill" the enormous amount of research now available.

## 9.5.

A set of realistic and easy to control tolerances should be established within a committee comprising by equal parts research men, high format designers and fabricators-erectors. IABSE and ECCS should be helpful in discussing this problem at the European or even worldwide level. The control of these tolerances could be restricted to a certain sampling (5 % ?) to be agreed upon by the parties. Anyway, continuous recording of measurements on all parts of a bridge at the factory during fabrication is unacceptable.

## 9.6.

Studies should be continued to investigate whether elastic shear lag (and possibly also stresses arising from restraint of warping are "eroded" by plastic action. These studies should comprise fatigue - or, at least, repeated loading - tests, in order to assess to which extent the conclusions apply to bridges.

## 9.7.

Systematic comparative computations should be undertaken to assess whether optimization requests the stocky stiffeners commonly used (especially in Great-Britain) or whether it is economical to "expand" the cross section, as explained in detail in the beginning of section 4.

## 9.8.

It would be extremely instructive to compare on a wide basis these realistic ultimate strength design rules that we are still awaiting with the provisional rules based on the conventional theory evoked in section 8.5., in order to see whether the increase in scientific accuracy is justified by a sufficient increase in safety and or by an economy of the total price of the structure (that is the price including the design expenses).

## 9.9.

Summarizing, the main question mark still is: To which extent are we entitled to take benefit of plastic redistribution in the case of bridges supporting moving loads ?

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## REFERENCES.

A. Linear plate buckling theory and critical appraisal.

- A1 KLÖPPEL, K. and SCHEER, J.: Beulwerte ausgesteifter Rechteckplatten. W. ERNST und Sohn, ed., Berlin, 1960.
- A2 KLÖPPEL, K. und MÖLLER, K.H.: Beulwerte ausgesteifter Rechteckplatten, Vol. 2. W. ERNST und Sohn, ed., Berlin, 1968.
- A3 MASSONNET, Ch.: Essais de voilement sur poutres à âme raidie. I.A.B.S.E. Publications, Vol. 14, pp. 125-186, 1954.
- A4 MASSONNET, Ch., MAZY, G. and TANGHE, A.: Théorie générale du voilement des plaques rectangulaires orthotropes, encastrées ou appuyées sur leur contour, munies de raidisseurs parallèles aux bords à grandes rigidités flexionnelles et torsionnelles. IABSE Publ. Vol. 20, pp. 223-262, 1960.
- A5 MASSONNET, Ch., MAS, E. and MAUS, H.: Essais de voilement sur deux poutres à membrures et raidisseurs tubulaires. IABSE Publ. Vol. 22, p. 183, 1962.
- A6 SKALOUD, M. and NOVOTNY, R.: Überkritisches Verhalten einer anfänglich gekrümmten gleichförmig gedrückten in der Mitte mit einer Längsrippe versteiften Platte. Acta Technica CSAV N° 2, 1965.
- A7 MASSONNET, Ch.: Poutres de grandes dimensions à âme pleine. Preliminary Report of the 8th Congress of IABSE, New-York, 1968.
- A8 MAQUOI, R. and MASSONNET, Ch.: Discussion of the report by Professor P. DUBAS entitled: Essais sur le comportement postcritique des poutres en caisson raidies. London IABSE Colloquium: Design of Plate and Box Girders for Ultimate Strength; Vol. 11 of the Reports of the Working Commission of IABSE, 1971, pp. 381-400 (Published in Zürich in July 1972, 464 pp.).
- A9 MASSONNET, Ch.: Neue Erkenntnisse und Theorien aus europäischen Forschungsarbeiten, DAST Berichtheft 3, 1975.
- A10 BEER, H.: Conclusions of Theme II (Thin-walled structures) New-York Congress of IABSE, 1968, Final Report, pp. 497-498.
- A11 TOPRAC, A.A.: Fatigue Strength of full-size hybrid girders. A Progress Report, Proceedings AISC, 1963.
- A12 MAEDA, Y.: Ultimate static strength and fatigue behaviour of longitudinally stiffened plate girders in bending. IABSE Colloquium, London, 1971, pp. 269-282.
- A13 ROUVÉ, B.: Calcul du comportement postcritique des plaques raidies par la méthode des éléments finis. Publ. N° 76-1 - Statique Appliquée et Constr. Métallique, Ecole Polytech. Fédér. Zürich, 165 pp., 1976.
- A14 MASSONNET, Ch.: Concluding Remarks of the Chairman. IABSE Symposium on Steel and Composite Structures for user needs, Dresden, 1975. Final Report (to be published).

- A15 MAQUOI, R. and MASSONNET, Ch.: Conventional design rules based on the linear plate buckling theory. Appendix to the ECCS Recommendations (to be published in 1976).
- A16 ECCS Manual on Stability: Chapter 6: Plate and Box Girders. Section 6.1.: Conventional Design Rules based on the linear Buckling Theory. ECCS, Editor, August 1976.
- A17 WOLMIR, A.S.: Biegsame Platten und Schalen. V.E.B. Verlag für Bauwesen, Berlin, 1962.
- A18 SCHEER, J. and NÖLKE, H.: The background to the future german plate buckling design rules. ICSPS, paper 21, London 1976.
- A19 JOHNSTON, B.G. : ed. Guide to Stability Design Criteria for Metal Structures, 3d ed. John WILEY and Sons, 1976.
- B. Lessons to be drawn from the four accidents to box girder bridges.
- B1 CICIN, P.: Betrachtungen über die Bruchursachen der neuen Wiener Donaubrücke, Tiefbau, Vol. 12, pp. 665-674, 1970.
- B2 SATTler, K.: Nochmals: Betrachtungen über die Bruchursachen der neuen Wiener Donaubrücke. Tiefbau, Vol. 12, pp. 948-950, 1970.
- B3 ROIK, K.: Nochmals: Betrachtungen über die Bruchursachen der neuen Wiener Donaubrücke, Tiefbau, Vol. 12, p. 1152, 1970.
- B4 HECKEL, R.: The fourth Danube Bridge in Vienna. Damage and Repair. Developments in Bridge Design and Construction. Crosby Lockwood, London 1972.
- B5 SHIRLEY-SMITH, H.: Report on Collapse of Milford Haven Bridge. Fatal Accident 2nd June 1970 (Expertise Report).
- B6 Report of Royal Commission into the Failure of West Gate Bridge, presented to both Houses of Parliament pursuant to section 7 of the West Gate Bridge Royal Commission act. 1970, Melbourne 1971.
- B7 MAQUOI, R. and MASSONNET, Ch.: Leçons à tirer des accidents survenus à quatre grands ponts métalliques en caisson. Annales des Travaux Publics de Belgique, 1972, n° 2 and Costruzioni Metalliche, 1973, N° 2 (in Italian).
- B8 BISSE, W.H.: On the cause of failure in the bridge Koblenz-Horchheim (in German). Tiefbau, Vol. 1, 1973.
- B9 ROIK, K.: Folgerungen aus der Schadensfällen im In- und Ausland. - DAST Berichtheft N° 3, April 1975
- B10 MAQUOI, R.: Essai de détermination des flèches initiales des panneaux comprimés raidis des grands ponts en caisson. IABSE Publications, Vol. 31-II, 1972, pp. 141 - 151.

# C. Plate Girders, Ultimate strength.

- C1 RODE, H.: Beitrag zur Theorie der Knickerscheinungen - Der Eisenbau, 1916.
- C2 WAGNER, H.: Ebene Blechträger mit sehr dünnem Stegblech - Zeitschrift für Flugtechnik und Motorluftschiffahrt, Vol. 20, 1920, p. 220.
- C3 BASLER, K. and THÜRLIMANN, B. : Strength of plate girders in bending. Journ. Struct. Div., ASCE, Proc. N° 2913, ST 6, p. 154, Aug. 1961.
- C4 BASLER, K. : Strength of Plate Girders in Shear. Journ. Struct. Div. ASCE Proc. N° 2967, ST 7.
- C5 BASLER, K.: Strength of Plate Girders under combined bending and shear. Journ. Struct. Div. ASCE, Proc., 1968, ST7, p.181, October 1961.
- C6 FUJII, T.: On an improved Theory for Dr. BASLER's Theory. New-York 1968 Congress of IABSE, Final Report.
- C7 W.C.II of IABSE: Proceedings of the London 1971 Colloquium: Design of Plate and Box Girders for ultimate strength. IABSE, Zürich 1972.
- C8 ROCKEY, K.C. and SKALLOUD, M.: The ultimate load behaviour of plate girders loaded in shear- I.A.B.S.E. 1971 Colloquium. pp. 1 - 19.
- C9 FUJII, T., FUKUMOTO, Y., NISHINO, F. and OKUMURA, T.: Research works on ultimate strength of plate girders and japanese provisions on plate girders design. IABSE 1971 Colloquium, pp. 21 - 48.
- C10 KOMATSU, S.: Ultimate strength of stiffened plate girders subjected to shear. IABSE Colloquium, pp. 49 - 65.
- C11 OSTAPENKO, A. and CHERN, C.: Ultimate Strength of Longitudinally stiffened plate girders under combined loads. IABSE 1971 Colloquium, pp.301 - 313.
- C12 BERGFELT, A.: Plate Girders with slender webs - survey and a modified calculation method. Summary in English of the Report n° II.2.2. to "Nordiske Forskningsdager for Stalkonstruksjoner", Oslo, 1973.
- C13 HÖGLUND, T.: Design of thin plate I girders in shear and bending with special reference to web buckling. Institutionen för Byggnadsstatik Kungl. Tekniska Högskolan, Stockholm 1973, N° 94.
- C14 DUBAS, P.: Zur Erschöpfungslast schubbeanspruchter Stehbleche. Professor STEINHARDT Festschrift, Karlsruhe, 1974.
- C15 SELBERG, A.: On the shear capacity of girder webs. IABSE Publications, Vol. 34-I, pp. 145-155, 1974.
- C16 STEINHARDT, O. and VALTINAT, G.: Theorie und Berechnung beulgefährdeter Vollwand - und Kastenträger, Technische Universität Hannover, Lehrstuhl für Stahlbau, Schriftenreihe, Heft 9.
- C17 PORTER, D.M., ROCKEY, K.C. and EVANS, H.R.: The collapse behaviour of plate girders loaded in shear. The Structural Engineer. August 1975, Vol. 53, N° 8.

- C18 DJUBEK, J. and SKALoud, M.: Postbuckled behaviour of web plates in the new edition of the Czechoslovak design specification. I.C.S.P.S., Session 3, p. 16, London, 1976.
- C19 ECCS Manual on Stability: Section 6.3.: Design of webs of plate and box girders. 29 pp. ECCS, editor, August 1976.
- C20 EVANS, H.R., PORTER, D.N. and ROCKEY, K.C.: Ultimate load behaviour of box girder webs. ICSPS, paper 14, London 1976.
- C21 ROCKEY, K.C.: The design of web plates for plate and box girders: a state-of-the-art report - ICSPS, paper 19, London 1976.
- C22 HERZOG, M.: Die Traglast unversteifter und versteifter, dünnwandiger Blechträger unter reinem Schub und Schub mit Biegung nach Versuchen. Der Bauingenieur, 49, 1974, H. 10.
- C23 GAYLORD, E.H.: Trans. A.S.C.E., Vol. 128, Part II (1963), p. 712.

#### D. Box girders.

- D1 DUBAS, P.: Essais sur le comportement post-critique de poutres en caisson raidies. IABSE 1971 Colloquium, pp. 367-379.
- D2 MAQUOI, R. and MASSONNET, Ch.: Non-linear theory of postbuckling resistance of large stiffened box girders. IABSE Publications. Vol.31-II, pp.91-140, 1971.
- D3 Steel box girders bridges. Proceedings of the International Conference organised by the Institution of Civil Engineers, London 13-14 February 1973. Published by the Institution of Civil Engineers, London.
- D4 Inquiry into the basis of design and method of erection of steel box girder bridges : Interim Design and Workmanship Rules (Merrison Rules): Parts I to IV - Her Majesty Stationery Office, London.
- D5 MASSONNET, C. and MAQUOI, R. : New Theory and Tests on the Ultimate Strength of Stiffened Box Girders. Published in Ref. D3.
- D6 DWIGHT, J.B. and LITTLE, G.H.: Stiffened Compression Panels. A design Approach. Cambridge University Technical Report N° CUED/C-Struct/TR 38 1974.
- D7 MURRAY, N.W.: Analysis and Design of Stiffened Plates for Collapse Load. The Structural Engineer, March 1975.
- D8 HORNE, M.R. and NARAYANAN, R.: An Approximate Method for the Design of Stiffened Steel Compression Panels. Proceedings of the Institution of Civil Engineers: Research and Theory: September 1975.
- D9 MAQUOI, R.: Theoretical and experimental study of the postcritical strength of the compressed stiffened flanges of large steel box girders (condensed from Doctoral Thesis). Publications of the Faculty of Applied Sciences, University of Liège, 1975.
- D10 MAQUOI, R. and MASSONNET, Ch.: Vérification expérimentale de la résistance postcritique des semelles comprimées raidies sur six poutres en caisson. IABSE Publications, Vol. 36-I, 1976.



- D11 DOWLING, P.J. and MOFFATT, K.R.: Parametric study of the shear lag phenomenon in steel box girder bridges. CESLIC Report BG17, 1972.
- D12 DOWLING, P.J. and MOFFATT, K.R.: Shear lag in steel box girder bridges. The Structural Engineer, October 1975, Vol. 53, N° 10.
- D13 ABDEL-SAYED, G.: Effective width of steel deck plate in bridges. Proc. ASCE, Journ. Struct. Div. Vol. 95, ST7, pp. 1459-1474, 1969.
- D14 DIN 1073 Stählerne Strassenbrücken - Berechnungsgrundlagen, July 1974.
- D15 MAQUOI, R. and MASSONNET, Ch.: Discussion of the reference D12 - The Structural Engineer, 1976 (to be published).
- D16 BILSTEIN, W.: Anwendung der nichtlinearen Beultheorie auf vorverformte mit diskreten Längssteifen verstärkte Rechteckplatten unter Längsbelastung. Doctoral Thesis, Technische Hochschule Darmstadt, 1973.
- D17 STEINHARDT, O.: Berechnungsmodelle für ausgesteifte Kastenträger. DAST Berichtsheft 3, April 1975.
- D18 RUBIN, H.: Das Tragverhalten längsversteifter, vorverformter Rechteckplatten unter Axialbelastung nach der nichtlinearen Beultheorie. Schriftenreihe Heft 1, Karlsruhe, 1976.
- D19 CHANG SUNG Pil: Beitrag zur Berechnung des nichtlinearen Tragverhaltens einer in Längsrichtung mit offenen oder geschlossenen Steifen verstärkten und durch Druck belasteten Rechteckplatten mit Vorverformungen bei Navierschen Randbedingungen. Doctoral Thesis, Stuttgart, 1976.
- D20 WALKER, A.C.: The postbuckling behaviour of simply-supported square plates. The Aeronautical Quarterly, Vol. 20, pp. 203-222, 1969.
- D21 WALKER, A.C. and MURRAY, N.W.: A Plastic collapse mechanism for compressed plates. IABSE Publications, Vol. 35-I, pp. 217-236, Zürich 1975.
- D22 DAVIES, P., KEMP, K.O. and WALKER, A.C.: An analysis of the failure mechanism of an axially loaded, simply supported plate. Proc. I.C.E., Part 2, 1975, Vol. 59, pp. 645-658.
- D23 ECCS Manual on Stability, Section 6.2.: Design of box girder compression flanges. Reporters P.J. DOWLING and S. CHATTERJEE, 24 pp.
- D24 HORNE, M.R. and NARAYANAN, R.: Ultimate strength of stiffened panels under uniaxial compression. ICSPS, paper 1, London 1976.
- D25 FRIEZE, P.A., DOWLING, P.J. and HOBBS, R.E.: Ultimate load behaviour of plates in compression. ICSPS, paper 2, London 1976.
- D26 MOOLANI, F.M. and DOWLING, P.J.: Ultimate load behaviour of stiffened plates in compression. ICSPS, paper 3, London, 1976.
- D27 MAQUOI, R. and MASSONNET, Ch.: Interaction between shear lag and post-buckling behaviour in box girders. ICSPS, paper 4, London, 1976.
- D28 DOWLING, P.J., MOOLANI, F.M. and FRIEZE, P.A.: The effect of shear-lag on the ultimate strength of box girders. ICSPS, paper 5, London 1976.



- D29 LALLY, A. and WOLCHUK, R.: American design practice for steel box girder bridges. ICSPS, paper 6, London 1976.
- D30 ROIK, K.: Effective breadth and shear lag in plate girder bridges with elastic and elasto-plastic material behaviour. ICSPS, paper 7, London 1976
- D31 CHATTERJEE, S. and DOWLING, P.J.: The design of box girder compression flanges. ICSPS, paper 8, London 1976.
- D32 STEINHARDT, O., VALTINAT, O. and RUBIN, H.: Limit state design rules for box girders. ICSPS, paper 9, London 1976.
- D33 WEX, B.P. and BROWN, C.W.: Limit states -real or imaginary in box girder bridges. ICSPS, paper 10, London 1976.
- D34 DUBAS, P.: Plated Structures with closed section stiffeners. ICSPS, paper 11, London 1976.
- D35 ROGERS, N.A. and DWIGHT, J.B.: Outstand Strength. ICSPS, paper 12, London 1976.
- D36 HARDING, J.E.; HOBBS, R.E. and NEAL, B.G.: Ultimate load behaviour of plates under combined direct and shear in-plane loading. ICSPS, paper 15, London 1976.
- D37 ELLIOTT, P., and ROCHESTER, T.A.: A background to research in plated structures. ICSPS, paper 17, London 1976.
- D38 ECCS Manual on Stability: Chapter 6: Plate and Box Girders. Section 6.2.: Design of box girder compression flanges (reporters P.J. DOWLING and S. CHATTERJEE) 24 pp. ECCS editor, August 1976.

#### E. Diaphragms.

- E1 Dept. of the Environment: Inquiry into the basis of design and method for erection of steel box girder bridges. Interim Design Rules, London 1973.
- E2 DOWLING, P.J.: Load bearing diaphragms in box girders. Working paper N° of Group 8/3 of ECCS.
- E3 JONES, J.P. and IRWIN, C.A.K.: Analysis of the centre diaphragm of a trapezoidal steel box girder. Transp. and Road Research Lab. Supplem. Report 101 UC, 44 pp. 1976.
- E4 CRISFIELD, M. and PUTHLI, R.: A finite element method applied to the collapse analysis of stiffened box girder diaphragms. ICSPS, paper 13
- E5 WOOD, J.G.M. and FLINT, A.R.: The design of box girder diaphragms. ICSPS, paper 18, London 1976.

- F. Miscellaneous. Plate girders without stiffeners, hybrid girders, effects of concentrated loads, special problems.
- F1 BERGFELT, A.: Studies and tests on slender plate girders without stiffeners. IABSE 1971 Colloquium, pp. 67 - 83.
- F2 HÖGLUND, T.: Simply supported long thin plate - I girders without web stiffeners, subjected to distributed transverse load. IABSE 1971 Colloquium, pp. 85 - 98.
- F3 HÖGLUND, T.: Strength of thin plate girders with circular or rectangular web holes without web stiffeners. IABSE 1971 Colloquium, pp. 353-365.
- F4 ROCKEY, K.C. and EL-GAALY, M.A.: Ultimate strength of thin-walled members under patch loading and bending. 2d specialty Conference on Cold-Formed Steel Structures. University of Missouri, 1975, p. 251.
- F5 BERGFELT, A.: The behaviour and design of slender webs under partial edge loading. ICSPS Paper 20, London 1976.
- F6 van DOUWEN, A.A.: Optimum design of plate girders. ICSPS, Paper 22, London 1976.

#### SUMMARY

After a brief summary of the tendency of research these last years, which is towards the development of ultimate strength, the author examines critically the linear buckling theory and emphasizes its shortcomings. Then, he reviews briefly the ultimate strength models presented for plate and box girders and compares their prediction with the full set of available experiments. After a brief review of the problems concerning shear lag, diaphragms and fabrication problems, he discusses the pro- and against ultimate design rules and shows the interest of provisional rules still based on the linear theory suitably adapted.

#### RESUME

L'auteur présente un bref résumé de l'évolution de la recherche au cours des dernières années, qui tend vers le développement des théories de la résistance à la rupture, puis il examine de façon critique la théorie linéaire du voilement et souligne ses faiblesses. Il rappelle brièvement les modèles de résistance à la rupture utilisés pour les poutres à âme pleine et en caisson et compare leurs résultats avec l'ensemble des expériences réalisées. Après un bref résumé des problèmes de "shear lag", de "diaphragme" et de fabrication, l'auteur considère les avantages et les inconvénients des règles de dimensionnement basées sur la résistance à la rupture; il souligne l'intérêt de règles provisoires basées sur la théorie linéaire adaptée de façon adéquate.

## ZUSAMMENFASSUNG

Nach einer kurzen Darstellung der Forschungsentwicklung der letzten Jahre, die in Richtung von Traglasttheorien tendiert, unterzieht der Autor die lineare Beultheorie einer kritischen Prüfung und unterstreicht ihre Mängel. Traglastmodelle für Vollwand- und Kastenträger werden besprochen und die entsprechenden Ergebnisse mit allen vorliegenden Versuchen verglichen. Nach einer kurzen Zusammenfassung der Probleme der verminderten Mitwirkung infolge Schubverzerrung, der Querscheiben und der Anfertigung erörtert der Autor die Vor- und Nachteile von Traglast-Bemessungsvorschriften und stellt fest, dass provisorische Vorschriften, die auf einer entsprechend angepassten linearen Beultheorie beruhen, von Interesse sind.

## VII

### Progress on Bridge Loading

Progrès dans la charge des ponts

Fortschritte bei der Erfassung der  
Belastung von Brücken

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Bridge Loading. Cambridge, 1-10 April 1975  
Organised by the British Group IABSE*

### General

Thirty six papers were contributed to the colloquium. The procedure adopted was that all papers were circulated to participants well before the date of the colloquium so that they could be read and digested, enabling the participants to be ready and prepared for the discussions at Cambridge. The procedure was eminently successful; all papers were in the hands of participants in adequate time and were clearly studied very thoroughly.

The various papers are individually of such value that it has been decided not to summarise them in the published report. They are available in full from the British Group. A list of the papers and authors is appended.

This report is a substantially abbreviated version of a much fuller report which is also available from the British Group. It attempts to review the substance and general conclusions of the very active discussions which took place over three days of concentrated application by the participants. It contains no extracts from the submitted papers for the reason given and does not attribute any statements to individuals since its object is to attempt to present a consensus of opinion. The author accepts full responsibility for his interpretation of this consensus.

Very considerable thanks and appreciation are due to the participants who produced much valuable work and devoted themselves to a very strenuous and intensive discussion.

All countries appear to have similar problems in respect of the classes of traffic which use their highways. Broadly, traffic can be classified into three groups.

- (a) Normal vehicles designed to conform to the general legal limits imposed in each country. These normal vehicle weights range in maxima up to some 400kN gross laden weight. This weight is fairly typical of most countries. In Ontario, Canada, however the permitted laden weight can be as much as 700 kN.

- (b) Extra Normal vehicles, typified by engineering construction equipment, the gross weight of which ranges up to some 1,500kN. The movement of this type of traffic is generally subject to some degree of control by law but enforcement of the controls appears in most countries to be fairly limited in its efficiency. There is, therefore, with these vehicles a not inconsiderable risk of them travelling on routes where it is undesirable they should be.
- (c) Abnormal Vehicles, which are special vehicles designed to carry indivisible loads of considerable weight such as electricity transformers and other heavy electrical plant. Loads up to some 6,000kN are to be considered in this group for which movement is in general closely controlled in most countries.

Whatever the form in which vehicular loading is presented for bridge design purposes it is a model and should be clearly recognised as such by those who apply it. The weight and disposition of vehicles varies from instant to instant and from bridge to bridge; the loading model must embrace the most severe effects of well defined categories of vehicles.

The view was taken that there should be one design loading model to represent traffic of categories (a) and (b) and another model to represent vehicles in category (c).

One of the defects of some design loading models in use in the past has been that while they catered for normal traffic reasonably well they did not do so satisfactorily for extra normal traffic; for medium and longer span bridges the main longitudinal members could sustain quite large overload effects due to these category (b) vehicles but short secondary members were severely limited. It was considered that any satisfactory traffic loading model for general application should be contrived to eliminate this defect and to produce a reasonably consistent overload capacity in all elements of a bridge.

With very few exceptions the view was taken that the most satisfactory form of model is a uniformly distributed load associated with one or two point loads. The point load or loads are intended to provide the necessary adjustment required to make it possible for one uniformly distributed load to be used for both bending and shear on the smaller elements of the bridge structures and also, of course, for the shorter span bridges.

Due to the mix of traffic, ranging from private cars (generally by far the largest number of vehicles using a highway) up through several gradations to the heaviest truck to be considered (generally a quite small proportion of the traffic) consideration must be given to the attenuation of the vehicular loading model as the loaded length becomes greater. On a short loaded length it is a reasonable expectation that it can be filled with closely packed vehicles of the heaviest type. As the loaded length increases the interspersing of lighter vehicles will reduce the equivalent intensity. The characteristic load is not sensitive to the nature and mix of the traffic for short and medium loaded lengths but does become very sensitive to these as the loaded length increases.

It is also the case that as the width of carriageway increases in terms of the number of traffic lanes available so too will the characteristic load decrease across the carriageway.

Several views were offered on how the loading model should be constructed to take these phenomena into account in respect of longitudinal attenuation;

- (A) That the intensity of the distributed load in a traffic lane should be taken as constant over short and medium loaded lengths and thereafter diminished in a smooth curve as the loaded length increases.
- (B) That a constant distributed load occupying a discreet loaded length of around 30 m should be taken and a series of these loaded lengths considered with gaps of no live loading between, the gaps progressively increasing in length as the total overall length under consideration increased.

The important consideration to be kept in view is that whatever device is adopted, the severe intensities associated with short and medium span structures must also be expected to occur on long structures and to occupy the same loaded length as is appropriate to the medium span bridge. These high intensities must be considered as occupying that part of the influence line with the largest ordinates.

While this is self evident when applying an arrangement of distributed load such as is described in (B), it can and should be applied with the arrangement described in (A) also.

In respect of transverse attenuation two devices were again presented;

- (C) That one or two lanes should be considered to be occupied by the full intensity of uniformly distributed load appropriate to the loaded length concerned and that all remaining lanes should be considered to be occupied by a stipulated fraction of the appropriate full intensity (say  $1/3$ ).
- (D) That the effect of multiplicity of lanes in the width of the bridge should be regarded simply as an extension of the treatment of the attenuation of uniformly distributed load in relation to the longitudinal loaded length. In applying this device the longitudinal lengths of each lane would be summed and the total load taken on the bridge would be represented by the product of this total loaded length and the appropriate intensity of distributed load associated with it. Where, however, elements of the structure were severely affected by shorter loaded lengths as, for example the length of one lane or part of a lane, the intensity of load appropriate to this particular loaded length would be applied within it and the remainder of the total for the whole bridge allocated to other lanes.

It remains to be established whether or not the patterns and disposition of traffic in adjacent lanes of a multi-lane highway are affected in the same way as is the case for increasing lengths of any single lane.

Although, the prevailing view was that a uniformly distributed load with one or two point loads provided the most satisfactory model there was, nevertheless, a strongly held conviction of a few participants that for short and medium loaded lengths it was most satisfactory to specify a pattern of trucks, reserving the distributed load concept to long loaded lengths.

#### Methods of Derivation of Loading Models

In the submitted papers there is a number of most excellent studies of statistical techniques and information presented. It remains, however, that there is much yet to do in the way of collection of data related to traffic weights and disposition on the highways and the formulation of trends of traffic behaviour. Among the aspects which call for study is the formation of convoys of heavy trucks, both as a consequence of the "properties" of different types of vehicle and as a result of the deliberate decision by organisations or drivers. By "properties" is meant relative operating speeds, manoeuvrability and other characteristics. It will no doubt also be necessary to extend the studies to take into consideration the "properties" of different kinds of highways. Studies are also desirable of traffic behaviour in special circumstances (accident, unexpected road block, throttling of traffic by unexpected reduction in the number of lanes at some point in an otherwise wide and free running carriageway). Basically there is also the need to collect data concerning the weights and spacings of axles and their sequence in different lanes of carriageways, taking into account that trucks are frequently <sup>not</sup> carrying their maximum capacity in terms of weight although they may be in terms of volume.

It was generally agreed that while probabilistic studies based on thoroughly researched data were of vital importance the derivation of a loading model could not be based on these alone. The final form and intensities of the traffic loading model would have to be based on the "credibility" approach supported by the probabilistic studies. These studies would contribute towards the important objects of;

1. Achieving a consistent standard of safety.
2. Ultimately establishing a quantified level of risk.
3. Reinforcing confidence in the adequacy of the loading model.

One of the serious difficulties in using the "credibility" approach is that on short loaded lengths where it is clearly feasible that a tightly packed group of the heaviest trucks could be present, the only way in which excess loading could be occasioned would be the overloading of vehicles. For this there is little room for doubt, but on long loaded lengths where the intensity of loading is diminished to reflect the attenuation of traffic it becomes possible to speculate on situations where the traffic might consist



of an exceptionally large number of the heaviest trucks which might become closely packed because of some blockage, while it might be that some of these trucks were grossly overloaded and these might unfortunately occupy the region where the influence line ordinates are largest. While this statement clearly is grossly exaggerated it nevertheless points up the contribution which probabilistic studies can make to (3) above.

Assuming that loading models are already in use, as they are in most countries, the development of well founded probabilistic studies related to various loaded lengths should make it possible to re-shape the model accordingly as the level of risk has been over or underestimated at different regions, thus achieving the objectives (1) or (2) above.

In this respect it is worth noting that for the small or moderate span bridge where the loading model is likely to be most realistic, quite large changes in design loads will have only minor effects on cost. On the other hand in large span bridges where the greatest uncertainty is, and the tendency is that the loading model is likely to have been made unduly severe, the cost of providing the strength to carry excessive traffic loading becomes substantial.

The problem remains at the present time, when the amount of statistical work done falls so far short of the desirable, how should an acceptable level of risk be established? The problem is not made simpler by the adoption of limit state design philosophy. It was considered that no serious attempt should be made to quantify the probabilities in numbers, but rather that the development should be made from experience of live load models used now and in the past. Are existing bridges safe for the levels of traffic we have today? If so, this state should be preserved. Comparisons can be made by equating the design loading effects when applied to established "permissible working stress" methods with the effects when applied to "limit state" methods and a suitable load factor derived. Since former methods generally used the same factor for dead loads as for traffic loads, while the latter method introduces low load factors for dead load, where there is a greater degree of certainty about its amount, it follows that the two methods can only be equated at one selected ratio of dead to live load and this must be chosen as a satisfactorily low value.

#### Vehicle regulation in law and changes in the future

A satisfactory standard of law enforcement in respect of the laden weights permitted on heavy trucks was considered essential, as was also the control of the weights and movements of these vehicles classified as extra normal and as abnormal.

The permitted weights of vehicles and the safe carrying capacity of bridges are intimately associated. It seems remarkable therefore that few states appear to use their highway bridge traffic loading model directly as a datum which also controls what may be permitted as maximum laden weights in their vehicle regulations. Only in Great Britain and Ontario it appears is there a deliberate formulation of permitted vehicle weights directly in terms of bridge loading.

In discussing the allied problem of the extent to which the loading model should anticipate future trends in the development of vehicles in terms of permitted weight it was generally conceded that this was something which could not be done in any developed country on a rational basis although some attempts had been made to do so on a short term basis to the extent of around 10%. The



fact is surely that any developed country has such a great capital investment in existing bridges that it is not conceivable that all of these should be made inadequate by a decision to introduce substantially greater carrying capacities.

In developing countries which presently may have comparatively light traffic it is possible to predict with a degree of confidence that traffic weights will trend towards those of developed industrialised societies and it is considered that the capital investment being made in new bridges should take this into account. Development and industrialisation can be seriously inhibited by inadequate bridge capacity.

Category C Vehicles All industrialised countries have the problem of moving exceptionally heavy, generally indivisible loads of industrial, frequently electrical equipment such as transformers, generators, large presses, even ships propellers, rudders, stern frames and the like. The needs of different countries tend to differ in accordance with the prevailing industrial activities and the existence within the country of other forms of transport such as railways and waterways capable of carrying these loads.

The extent to which highway bridges should be constructed to cope with these is very much a matter of the economics of each country. Few, if any of these loads are indivisible in the absolute sense, but simply are more cheaply and satisfactorily built in some factory equipped to construct them economically. To what extent bridges and routes should be designed to carry such loads is a matter of balancing the economics of constructing an adequate route against these other considerations, giving due account to the considerable nuisance these loads are to other highway users.

The number of these vehicles in any country is not large and they are generally of much the same configuration. Because of this the most appropriate model to be used for bridge design is an idealised vehicle. The movement of these vehicles on the roads is normally very strictly controlled; given the extent to which this control is reliable it is open to decide the extent of normal traffic which ought to be considered to be with these loads on bridges.

#### Dynamic Effects

Braking Forces There appears to be a very wide variation in the specified requirements of various countries. It was considered that this was an area where a review of these requirements was desirable. The increased adhesion possible between road surface and vehicle, the increased speeds of heavy vehicles and the use of elastomeric bridge bearings and piers which flex to accommodate temperature movements of the deck make it desirable that adequate braking forces should be specified. Two aspects of traffic should be considered, the first being several heavy trucks following each other at a speed appropriate to them and spaced out as they would be at that speed. An emergency application of brakes in the first truck would be followed by a similar application successively in the following trucks so that over a calculated period of time several trucks would exert the maximum braking force simultaneously. The second aspect would be the collision of one fast moving heavy truck with some other stationary but substantial truck or other object which might be disposed in such a way that progressive collapse of the latter would not dissipate a large proportion of energy.

Centrifugal Forces For much the same reasons as for braking forces a review of these was desirable. The succession of heavy trucks suggested for that effect would also be an appropriate condition to be considered for centrifugal forces.

Impact Effects Defining these as the outcome of dropping a mass on to a surface and also the sudden application of mass to an element, the former could vary quite considerably from country to country, depending on the standards of road construction and maintenance.

Little study appears to have been done on the effect of sudden application of loads to elements with very short loaded lengths, some of which may in fact have a cantilevered form where a wheel may exert its maximum effect at the instant of its first contact with the element (plates at expansion joints are an example); further investigations into this aspect are desirable.

Vibration and Damping There was general agreement that impact loading and dynamic response, though closely related should be treated separately so far as the effects on a bridge and its elements were concerned. The specification of a standard impact factor together with a maximum permitted deflection per unit of span is not considered to be an adequate or satisfactory check for the dynamic response of a bridge.

The calculation of the natural frequency should constitute part of the normal design procedure. Suitable approximate methods are given in papers submitted. Dynamic response can lead to the equivalent of an increment in vertical load which has been treated as part of the impact factor but preferably should be considered separately; where the vibration mode of the element is below 4.5Hz the value of this vertical increment of load can be substantially increased.

Vibration is of particular significance on footbridges where discomfort and alarm may be caused to the user. Tolerance levels are discussed in submitted papers.

The damping capacity of bridge structures has not been adequately researched and knowledge in this area is severely limited. Further work in this subject is strongly recommended and should be rewarding.

Fatigue Dealing first with stress cycles due to the dynamic response to vehicles, surveys of heavy vehicle behaviour have shown that with normal traffic flow there is little interaction due to the pressure of several vehicles. One stress cycle per vehicle with a 6% amplification of the static stress (giving a 1.2 factor on damage) would provide a reasonable basis in this respect.

The random variable stress cycles due to the passage of traffic can be related to design strengths derived from sinusoidal constant amplitude data using either Miner's cumulative damage rule or the Root mean square-stress range relationship. Both methods are dealt with in submitted papers.

Load Spectra should be based on observed national traffic and vehicle load conditions. These require to be extensively and thoroughly studied and reliable observations made of vehicle spacings, range of proportions of maximum load carried, alignment of successive vehicles behind each other and so forth.

It is believed that there is a strong tendency to make cumulative over-estimates of the stress ranges when making assessments a priori from limited data. The view was expressed that the load spectrum should vary in accordance with the locale of the bridge and that it should vary in accordance with the span.

The fatigue threshold is not well defined under high cycle ( $10$  to  $100 \times 10^6$ ) variable and constant amplitudes and further research is desirable in this area. So too is the need to develop techniques in fatigue monitoring and crack detection having practical application to bridges. Since the pattern of variable stress cycles and the number of cycles cannot be predicted with any degree of precision the same applies to the prediction of the initiation of cracks. Currently available monitoring devices (magnetic and acoustic instruments) have not been effective and painting which is essential to prevent corrosion obscures any fine cracks effectively, thus it is unlikely that any crack will be visually observable until it has opened quite significantly. It was agreed that some sort of displacement induced stress indicator should be developed towards this object and installed in steel bridge structures.

It was emphasised that strength in fatigue relied essentially on good detailing. Specifications should be framed to encourage designers to use good details and stringent quality control should be exercised at all stages during fabrication and erection. With these provisos it was generally felt that fatigue was probably not such a serious problem as it was thought to be by many authorities.

So far as corrosion fatigue is concerned it was considered that in normal environments with reasonable maintenance this was not a matter for concern.

The question of the design life of bridges was discussed. Several countries do not appear to specify this. It is, of course, necessary in dealing with fatigue in order to assess the number of cycles of stress to be considered. It is also essential in limit state design in order to establish partial factors which are time related. Some participants were, however, of the opinion that for the latter purpose the "life" could be taken as substantially less than the planned life of the bridge.

Collisions with Piers and Parapets Useful contributions were made on this subject. These deal with the control and containment of light vehicles such as private cars and also heavy trucks, but a great deal more work and study is required in the latter field. Calculation of the resistance to collision using dynamic methods related to energy dissipation is the most attractive approach to providing realistic and flexible solutions for specific situations as opposed to the rather arbitrary requirement of a strength to withstand a static force.