RAPPORT DE SYNTHÈSE / ZUSAMMENFASSENDER BERICHT / SUMMARY REPORT

0. INTRODUCTION.

The various items examined at the Colloquium have been arranged in the following order :

Sec. 1. Transversely stiffened plate girders :
- 1.1. Ultimate shear strength
- 1.2. Ultimate bending strength
- 1.3. Ultimate strength under combined bending and shear.

Sec. 2. Longitudinally stiffened plate girders.

Sec. 3. Girders without intermediate stiffeners

Sec. 4. Hybrid girders

Sec. 5. Fatigue problems

Sec. 6. Box girders

Sec. 7. Special problems :
- 7.1. Finite element approach
- 7.2. Web crippling under transverse loads
- 7.3. Plate girders with web holes
- 7.4. Girders with curved webs
- 7.5. Curved girders.

Numbers within brackets refer to the list of Colloquium reports placed at the end of present report. This list has been arranged in the alphabetic order of participating countries. Numbers within parentheses correspond to other research papers given in references.

1. TRANSVERSELY STIFFENED PLATE GIRDERS.

The first model for representing the behaviour of a plate girder with flexible flanges at ultimate load was developed by BASLER and THURLIMANN in 1960. Since that time, it has been incorporated into the American AISC (1) and AASHO (2) Specifications. Several other countries are on the verge of incorporating this design concept in their Specifications.
This pioneering work is represented to this Colloquium by the summary report of BASLER [15]. The initial BASLER-THURLIMANN model will therefore be considered as the basis for the discussions of the Colloquium and is not discussed per se in this Summary. It assumes that the shear strength is composed of the buckling strength of the web plus the postbuckling strength of the web represented by the formation of a tension field band. The limiting condition is given by yielding of the web within the band. One of the aims of the Colloquium is to improve and extend this concept.

1.1. TRANSVERSELY STIFFENED PLATE GIRDERS-ULTIMATE SHEAR STRENGTH.

New test data have been provided by ROCKEY and SKALOUD [5], KOMATSU [10] SKALOUD [17], CLARK and SHARP [21], OSTAPENKO and CHERN [23] and STEINHARDT and SCHROTER [27].

Several authors have proposed new ultimate strength mechanisms involving incomplete diagonal tension fields which are more refined than the original scheme proposed by BASLER [15].

FUJII [8a] gives a short summary of the theory he presented in 1968 at the New-York Congress of IABSE. This theory, which assumes that the web is fixed along the flanges and simply supported at the stiffeners, incorporates the effect of the strength of the flanges by a plastic beam mechanism under a uniformly distributed load. FUJII also provides [31] a numerical comparison of the ultimate load given by the various theories with available experimental results.

The theory presented by ROCKEY and SKALOUD [5] assumes that, for normal construction, the edges of the web are simply supported. However, in the case of tubular flanges, the use of a fixed support condition would be assumed. The theory is based upon the development of a beam type mechanism in the flanges and thereby allows for the influence of the flange rigidity upon the collapse load.

The theory proposed by KOMATSU [10] assumes the same web boundary conditions as FUJII. It allows for the influence of flange rigidity by allowing the formation of a plastic beam mechanism under bi-linear varying transverse loading.

OSTAPENKO and CHERN [23] include the effect of the flanges through the use of a frame (panel) mechanism. As in models proposed by FUJII and KOMATSU, the web is assumed to have fixed - simply supported boundary conditions.

It is remarkable that, in spite of considerable divergence in basic assumptions, all these approaches give acceptably good correlation with test results, on symmetrical girders. However, the method proposed by OSTAPENKO and CHERN [23] also applies to unsymmetrical girders, that is, girders having flanges of unequal area.

CLARK and SHARP [21] develop a mathematical model which superimposes three different stress fields. Their analysis does not take into account the effect of the formation of plastic hinges in the flanges, but does attempt to show the effect of elastic deformation of the flanges on web behaviour. CLARK and SHARP, in addition, provide detailed design guides for girders made of aluminium alloy.

STEINHARDT and SCHROTER [27] give a description of how the web stress distribution is influenced by the elastic deformation of the flanges. They suggest [37] an analytical approach based on this concept.

In connection with the above problem, attention must be drawn to the constructive remarks of OSIPOV [19] concerning the effect of the degree of unfairness in fabrication upon the ultimate strength of plate girders subjected to shear.

1.2. TRANSVERSELY STIFFENED PLATE GIRDERS-ULTIMATE BENDING STRENGTH.

New test data on the behaviour of plate girders subjected to bending have been presented by FUKUMOTO [8b]. He has paid particular attention to the variation of the effective width of the compressed part of the web under increasing load. In addition, the new tests executed by MAEDA [9] give further information on the same problem.

In his contribution [8a] , FUJII gives a formula for the ultimate bending strength of unstiffened panels based on yielding of the compression flange. FUKUMOTO [8b] studies the effective width of the web plate in the postbuckling range. He shows that the ultimate moment can be determined by using lateral torsional buckling theory if the effect of residual stresses is included (3).

A study was carried out by NISHINO and OKUMURA [8c] on large size rolled I beams with a depth of 900 mm, in order to study the magnitude and distribution of residual stresses inherent in the beams and their effect on the moment carrying capacity of the beams.

1.3. TRANSVERSELY STIFFENED PLATE GIRDERS-ULTIMATE STRENGTH IN BENDING AND SHEAR.

New test data have been presented by GACHON [4].

New theories have been proposed ([6],[8],[23]) and evaluated by comparison with the available test data.

In his contribution [8a], FUJII proposes criteria for constructing a polygonal interaction curve combining the effects of bending and shear. Using this curve, FUJII obtained good agreement with the experimental data obtained at Lehigh University and reported by BASLER (4).
From first principles, one merit of FUJII's approach over BASLER's theory is that the first side AB of the polygonal curve is slightly sloping toward the shear axis, instead of being horizontal as in BASLER's approach. However, the available experimental results are too few to decide conclusively between the two approaches and clearly further tests are needed.

The only theoretical models which allow combining the effects of shear and bending in a continuous manner are those proposed by ROCKEY [6] and OSTAPENKO and CHERN [23]. Both models incorporate the basic features of their respective shear models but modify them to include the effect of bending on the web buckling stress, on the plastic capacity of the flanges and of the ultimate strength criterion.

2. LONGITUDINALLY STIFFENED PLATE GIRDERS.

In connection with longitudinally stiffened plate girders, predominant interest at the colloquium was on the bending strength although other types of loading were also considered.

In his experimental study, MAEDA [9] demonstrates the beneficial effects which can be obtained on the bending strength by employing longitudinal stiffeners and tubular compression flanges. Due to the high torsional rigidity of such a flange, it fails by lateral buckling instead of by lateral torsional buckling.

COOPER [22] demonstrates that BASLER-THURLIMANN's theory can be applied to higher values of web slenderness ratio than originally proposed. He mentions that one test girder with a slenderness ratio of 751 behaved in accordance with the theory. COOPER [22] shows that longitudinal stiffeners can contribute to bending strength by controlling lateral web deflections in the compressed portion of the web, thereby eliminating the need for the reduction in the ultimate moment. (see further reference to this point in Sec. 5 devoted to fatigue). According to COOPER, if the longitudinal stiffeners are not proportioned to remain straight up to ultimate load, then their influence should be ignored.

OSTAPENKO and CHERN [23] determine the ultimate bending strength defined by buckling of the compression flange column. They use the same approach as COOPER (5) with respect to longitudinal stiffeners. In the case of a one-sided stiffener, beam-column analysis is recommended.

The same design method is advocated by BASLER (4), who remarks that this concept will in general require larger longitudinal stiffeners than those required by the linear plate buckling theory. It is however not correct, remarks BASLER, to take advantage of the stress redistribution occurring after the critical stress has been surpassed, and simultaneously to design the panel framing members according to the linear theory. As the loading capacity of a plate girder does not bear a fixed ratio to the critical loading of a web panel, it is also not correct, according to BASLER, to base this increased requirement about the stiffeners on plate buckling calculations only. Either stiffeners must fulfill their function up to the collapse of the girder, or they should not be introduced into the calculations.

This approach should be compared with that proposed by MASSONNET (6) and endorsed by OWEN, ROCKEY and SKALOUD (7), namely to adopt for the relative rigidity $\gamma = EI_s/bD$ of the stiffener a definite multiple m of the theoretical optimum rigidity γ^* :

$$\gamma = m\gamma^* \qquad (1)$$

OWEN, ROCKEY and SKALOUD (7) have shown that, for longitudinal stiffeners rigid up to collapse, that is with m = 6 to 8 in equation (1), the ultimate bending moment of a girder reinforced by longitudinal stiffeners becomes equal to the plastic moment of a section composed of the part of the cross section subjected to tension plus the compressed flange, the longitudinal stiffeners and adjacent portions of the web determined by an effective width formula.

In the case of flexible longitudinal stiffeners, the problem of determining the ultimate strength becomes exceedingly difficult and has not been sufficiently studied.

The shear strength of a longitudinally stiffened plate girder is determined by FUJII [34], ROCKEY [6], KOMATSU [10], and OSTAPENKO and CHERN [23] by adding the shear strengths of the individual subpanels as determined using their respective theories developed for transversely stiffened girders. This approach was originally proposed by COOPER [6], but he did not consider the contributions made by the flanges and longitudinal stiffeners.

ROCKEY [6] proposes to obtain the ultimate strength of longitudinally stiffened girder subjected to a combination of bending and shear by using the same criterion as for transversely stiffened girders. OSTAPENKO and CHERN [23] require compatibility of deformations between subpanels. Both papers ([6],[23]) define a continuous interaction relationship between bending and shear. OSTAPENKO and CHERN's theoretical and experimental results indicate that addition of a longitudinal stiffener may increase the strength of a girder much more substantially under combined loads than under pure shear or bending.

Much more work is needed to define the role and the strength of the longitudinal stiffeners, especially if they start deflecting before the ultimate capacity of the girder panel is reached.

3. GIRDERS WITHOUT INTERMEDIATE STIFFENERS.

The Swedish Provisional Rules give rules for the design of plate girders without intermediate stiffeners. They are valid for welded plate girders in roof construction subjected to static loads. The rules include a set of fabrication tolerances. BERGFELT (10) presented in 1968 at the New-York IABSE Congress a paper reporting on tests on this type of girders and he has further dealt with these studies in part of his report to the Colloquium [12].

New tests on this type of girder are presented at the Colloquium by HÖGLUND [13]. HÖGLUND also proposes a lattice truss analogy for determining the ultimate strength.

4. HYBRID GIRDERS.

Much progress has been made recently in this field in the United States (11). Design rules are proposed in the 1969 AISC Specification on Steel Buildings (1) as well as in the AASHO Specifications (2). AISC rules apply only to webs with $b/t < 70$.

Much of the earlier work, which dealt with webs having low b/t ratios, may be found in papers by CARSKADDAN (12) and TOPRAC (13). Further tests on webs having b/t ratios up to 300 and with longitudinal stiffeners are presented at the Colloquium by MAEDA [9], [32].

Analytic approaches for high web slenderness ratios are proposed by BASLER (4), by FUJII [8a] and by OSTAPENKO and CHERN [23].

5. FATIGUE PROBLEMS.

New significant fatigue tests are presented by MAEDA [9], who classifies the various types of fatigue cracks observed. This author shows that the use of strong longitudinal stiffeners and of a tubular type of compression flange reduces greatly the "breathing" of the web and achieves an improved behaviour of the girder.

Fatigue seems to be of special concern in the case of hybrid girders, because the ductility of the web steel has been reduced by plastic deformations. Additional fatigue tests on hybrid girders would be therefore particularly welcome.

6. BOX GIRDERS.

Only one report is devoted to this theme, that of DUBAS [16]. The failures involving large steel box girder bridges which have occurred recently emphasize the need for more research in this nearly completely neglected field.

The striking result of DUBAS's first test is that a compressed flange reinforced by stiffeners which only have the theoretical rigidity γ^* necessary to ensure that they remain straight when the panel buckles exhibits a very variable and unsatisfactory stress distribution. The consequence of this is that the mean collapse stress $\bar{\sigma}$ is less than the critical stress σ_{cr} given by the linear buckling theory for an ideally perfect flange. In DUBAS's second test [33], which uses the same size plate as in the first one but with stiffeners having rigidity five times that of those used on the first test, the resulting stress distribution is nearly uniform, with small waves between the stiffeners. As a result, the strength of the compressed flange was increased by 85 per cent.

DUBAS considers that longitudinal stiffeners should be designed so as to remain straight up to collapse and recommends to use stiffeners with relative rigidities $\gamma = 5\,\gamma^*$.

This report draws attention to the fact that the low safety factors used at present with the classical design approach based on linear buckling theory, while they may be satisfactory for plate girders, are certainly too low for the compressed flanges of box girders and should be increased.

The contribution to the Prepared Discussion presented by MASSONNET and MAQUOI [29] emphasizes these points.

These authors show that the low mean collapse stress obtained by DUBAS can be demonstrated theoretically, which may explain the recent collapse of the longitudinally stiffened box girders of the Vienna bridge (14). They recommend therefore to increase for box girders the safety factor against buckling. (See in this connection [38] and [39]).

Much additional research is needed in this field, to develop a theory which would be able to predict the strength of compressed stiffened plates, not only reinforced by stiffeners remaining straight up to collapse, but also by "flexible stiffeners", because it has not been proved that the use of the latter type of stiffening does not correspond to the most economical solution.

7. SPECIAL PROBLEMS.

7.1. FINITE ELEMENT APPROACH.

GACHON [4] gives an approximate analytical method using the finite element technique, for thin anisotropic stiffened plates with initial deformations. This analysis takes into account the large displacements of the plate as well as of the stiffeners. The computer program is used, at the present time, as an experimental tool; in the future it is expected to be extended to the plastic range.

7.2. WEB CRIPPLING UNDER CONCENTRATED LOADS.

In Part II of his report [12], BERGFELT investigates the influence of flange stiffness on the crippling load. He also states that, for girders with slenderness ratios in excess of 150, the crippling load does not depend as much on the web depth as predicted by the elastic theory. SKALOUD and NOVAK [36], examining the ultimate behaviour of transversely stiffened girders subjected to a transverse load applied between the stiffeners, also demonstrate that the load carrying capacity of the web is affected by the rigidity of the flanges. ROCKEY and EL-GAALY [30] show that a linear relationship exists between the ultimate carrying capacity of girders subjected to a concentrated load and their buckling load.

7.3. WEBS WITH HOLES.

HÖGLUND [14] presents a paper dealing with the ultimate behaviour of long unstiffened plate girders of the type discussed in Section 2 when the web contains holes of various shapes. The diagonal tension field of the latticed truss model proposed by HÖGLUND is shown to provide failure loads in close agreement with experimental values. It would be of interest to see this approach extended to girders containing more closely spaced openings.

7.4. GIRDERS WITH CURVED WEBS.

Girders with curved webs are discussed in report [18] by ILYASEVITCH and KLUJEV. Except for the studies on curved panels conducted by the aircraft industry, only limited research has been conducted on girders with curved webs.

ILYASEVITCH and his collaborator have used the MARGUERRE non-linear equations and, using a computer, have succeeded in producing design charts. In addition to their theoretical study, they have conducted a limited experimental program, which indicates that their theory overestimates slightly the collapse capacity of the girders. It is of interest to note that if, generally, the curvature produces an increase in buckling load, there is an accompanying decrease in the postbuckling reserve strength.*

7.5. CURVED GIRDERS.

DABROWSKI and WACHOWIAK [11] consider the behaviour of a panel of a thin web which is curved longitudinally to a constant radius. The authors consider their linear analysis as a first step towards a more comprehensive investigation of the problem. As a consequence, the present study, while providing some interesting features, is not sufficiently well advanced to result in the development of suitable design rules.

Remark:
Some contributions mentioned herein are not included in the present Report.

LIST OF REPORTS PRESENTED AT THE COLLOQUIUM.

[2]	G. BURGERMEISTER and H. STEUP	Zum Einfluss verzinkungsabhängigen Vorbeulen auf die Tragfähigkeit von Vollwandträgern.
[3]	H. GACHON	Analyse du comportement des plaques minces raidies dans le domaine des grands déplacements.
[4]	H. GACHON	Essais sur une poutre à âme mince et à membrures symétriques.
[5]	K.C. ROCKEY and M. SKALOUD	The Ultimate Load Behaviour of Plate Girders Loaded in Shear.
[6]	K.C. ROCKEY	The Ultimate Load Behaviour of Stiffened Plate Girders Loaded in Shear and Bending.
[7]	G. CERADINI	Postbuckling Analysis of Stiffened Elastic Plastic Plate Girders by Finite Element Methods.
[8]	T. FUJII, a Y. FUKUMOTO b F. NISHINO and c T. OKUMURA d	Research Works on Ultimate Strength of Plate Girders and Japanese Provisions on Plate Girder Design.
[9]	Y. MAEDA	Ultimate Static Strength and Fatigue Behaviour of Longitudinally Stiffened Plate Girders in Bending.
[10]	S. KOMATSU	Ultimate Strength of Stiffened Plate Girders Subjected to Shear.
[11]	R. DABROWSKI	Stresses in Thin Cylindrical Webs of Curved Plate Girders.
[12]	A. BERGFELT	Studies and Tests on Slender Plate Girders without Stiffeners.
[13]	T. HÖGLUND	Simply supported Long Thin Plate I - Girders without Web Stiffeners subjected to Distributed Transverse Load.
[14]	T. HÖGLUND	Strength of Thin Plate Girders with Circular or Rectangular Web Holes without Web Stiffeners.
[15]	K. BASLER	Vollwandträger : Berechnung im überkritischen Bereich.

[16] P. DUBAS	Essais sur le Comportement Post-Critique de Poutres en Caisson Raidies.
[17] M. SKALOUD	Ultimate Load and Failure Mechanism of Webs of Large Width-to-Thickness Ratios, Subjected to Shear and Attached to Flanges of Various Flexural Rigidities.
[18] S. ILYASEVITCH and B.N. KLUJEV	Stabilität der elastischen Zylinderbauplatte bei Querbiegung eines dünnwandigen Stahlträgers mit doppelter X - förmiger Wand.
[19] S.V. OSIPOV	Effect of Initial Distorsions on the Carrying Capacity of Welded I - Girders.
[20] P.S. CARSKADDAN	Research on Hybrid Plate Girders.
[21] J.W. CLARK and M.L. SHARP	Limit Design of Aluminium Shear Webs.
[22] P.B. COOPER	The Ultimate Bending Moment for Plate Girders.
[23] A. OSTAPENKO and C. CHERN	Strength of Longitudinally Stiffened Plate Girders Under Combined Loads.
[26] B.T. YEN and J.S. HUANG	Some Considerations on the Stiffener Requirements of Plate Girders.
[27] O. STEINHARDT and W. SCHRÖTER	Das überkritische Verhalten von Aluminium - Vollwandträgern mit Quersteifen.
[28] K. KLÖPPEL and W. BILSTEIN	Das Torsionverhalten von Stäben mit dünnwandigen, offenen Profilen bei Berücksichtigung grosser Verformungen und Eigenspannungen.
[29] C. MASSONNET and R. MAQUOI	Discussion of the Report by Professor P. DUBAS : Essais sur le Comportement Post-Critique de Poutres en Caisson Raidies.
[30] K.C. ROCKEY and M.A. EL-GAALY	A Note on the Ultimate Strength of Plates when Subjected to Discrete (Patch) Loading.
[31] T. FUJII	Comparison between the Theoretical Shear Strength of Plate Girders and the Experimental Results.
[32] Y. MAEDA	Additional Study on Static Strength of Hybrid Plate Girders in Bending.
[33] P. DUBAS	Complément au Rapport N° 16: Essais sur le Comportement Post-Critique de Poutres en Caisson Raidies
[34] M. SKALOUD	Prepared discussion in regard to the Ultimate Load Behaviour of Webs in Shear.

[35] M. SKALOUD Prepared Discussion of the Report presented by Professor P. DUBAS: "Essais sur le comportement post-critique de poutres en caisson raidies".

[36] M. SKALOUD Prepared Discussion regarding the Post-buckled Behaviour and Incremental Collapse of Webs subjected to Concentrated Loads.

[37] O. STEINHARDT and W. SCHRÖTER Addition to the Report : Postcritical Behaviour of Aluminium Plate Girders with Transverse Stiffeners.

[38] K. KLÖPPEL English translation of excerpts of pages 13, 14 and 15 of the book by K. KLÖPPEL and K.H. MÖLLER: Beulwerte ausgesteifter Rechteckplatten, Vol. II, W. ERNST Ed., 1968.

[39] F. LEONHARDT Excerpts of a letter of Professor F. LEONHARDT to Professor C. MASSONNET reproduced with the permission of Prof. LEONHARDT.

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(12) CARSKADDAN, P.S.: Shear Buckling of Unstiffened Hybrid Beams. Journ. Struct. Div., Proc.ASCE, Vol. 94, N°ST8, August 1968 .

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