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IV

Structures in steel and light alloys

Tragwerke aus Stahl und aus Leichtmetall

Construções de aço e de ligas leves

Constructions en acier et en alliages légers

General Report – Generalreferat – Relatório Geral – Rapport Général

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The original plan for Theme IV contemplated the division of the subject into four sub-themes, viz:

IVa – *Light construction in steel*
IVb – *Construction in light alloy*
IVc – *Various structures (Power transmission poles a. s. o.)*
IVd – *Maintenance of metal structures*

Six papers have been submitted in this field. It is proposed here to briefly review these papers and attempt to draw whatever conclusion the results of the studies suggest.

IVa – No papers presented under this heading.

IVb – Paper by K. C. ROCKEY, M. Sc., Ph. D., A. M. I. C. E., entitled «*The design of web plates of light alloy plate girders*».

This paper presents the results of a very extensive experimental investigation of the behavior of the webs of plate girders composed of high-strength aluminium alloy designated in the British Standards as H10WP.

The test specimens were comparatively small models with a clear web depth of 12″ and a stiffener spacing of 4-7/8″. Both single and double angle stiffeners were used and a total of some 200 plate-stiffener combinations were studied. In general, all specimens were tested to destruction, since a prime objective of the investigation was to determine the post-buckled action of the web. Also many strain gauge readings were taken and lateral deflections (dishing) of the web observed and measured.

In justification of the rather ambitious experimental program carried out the author mentions the following points:

a) Possibly due to the increasing use of shear resistant web plates in airplane structures, much research, theoretical and experimental, has been devoted to the problem of the buckling of plates in shear. The general form of the equation for the buckling shear stress, Tcr, has been established (by Timoshenko and others) as

$$Tcr = \frac{K\pi^2 D}{d^2 t}$$

where D is the flexural ridigity of a unit width of web plate and d and t are the clear depth and the thickness, respectively. K is a constant, to be determined, analytically or experimentally, for the given conditions of the problem. Its value depends not only on the stiffener spacing, b, but on the ratio of the flexural rigidity of the stiffener to the flexural rigidity of a width of plate equal to the stiffener spacing. In fact, the heart of the problem is to determine the relationship between K and a dimensionless parameter $\gamma = \frac{EI}{bD}$.

b) Efforts to determine the relation of K to γ theoretically have met with the difficulty that in order to render the problem amenable to mathematical treatment, various simplifying assumptions must be made which vitiate the results and render them unsafe for practical use without experimental verification.

c) While several attempts have been made to determine the relation of K to γ experimentally, in the author's opinion none of these has been entirely successful, the principal value of the studies being the negative one of showing that the theoretical values given by Timoshenko and by Way are incorrect.

The author's objective was to carry out an experimental investigation that would give values for K suitable for design use.

He obtains a set of empirical equations giving K in terms of γ for various conditions and later presents a set of equations for Tcr which may be used in design.

The author recommends that whenever the buckling stress is less than the basic permissible working stress, the web be designed to act in the post-buckled stage. The type of structural behavior in this case is wholly different from the pre-buckled stage in that the web structure now simulates the action of a truss, the stiffeners serving as posts and web tension as diagonal. Designing in accordance with the author's recommendations results in much higher permissible stresses than are now commonly used.

It is noted that in some cases the bulging of the web in the post-buckled state may be undesirable for aesthetic reasons and that this, rather than the effect on the ultimate carrying capacity, will often govern the permissible stress.

The proposed design formulas reflect this view.

In addition to the investigation of shear buckling the author has also made a rather extensive study of the buckling of thin webs subjected to pure bending stresses. These tests were also carried into the post-buckled stage. It is the author's conclusion that «for girders of normal proportions failure was, as expected, due to flange collapse and not due to any form of web failure».

While the design formulas proposed can only be *directly* used for aluminium alloy of the type used in the test pieces, deductions that may be drawn from the general behavior of the girders should have a wide application.

IVc – (1) The paper by Messrs. FERRY BORGES and ARGA E LIMA entitled «*Experimental study of towers for high tension lines*» presents the results of a very interesting series of tests on electrical transmission towers. Some of the tests were on 1/6 and 1/7 scale models and some on full-sized prototypes.

Tests were made for vertical and transverse loads, both symmetrical and unsymmetrical. For the former, close agreement was found between measured and calculated stresses, while for the latter there was in some cases a large discrepancy, the actual stresses being much less than the computed stresses. The authors state that this was due to the fact that the analytical method used in the stress computation was based on unsuitable hypotheses. A revised method was later devised which closely agreed with the measured results.

Neither method is adequately described, so no general conclusions can be drawn.

On both models and prototype tests were apparently carried to failure and in this process a number of weak details were discovered and eliminated.

(2) Paper by Mr. H. SAUNDERS, A. I. Sruct. E., entitled — «*Castellated construction*».

This paper describes a novel procedure for increasing the depth (and therefore the bending resistance) of rolled sections, without increasing the weight, by means of a zig-zag horizontal cut in the web which leaves a pair of unsymmetrical toothed sections which are then shifted to bring the points of the teeth into contact and so welded. This gives a deeper beam of the same weight with a perforated web.

The advantages are obvious. As a matter of practical convenience the depth increase is usually limited to 50 % and the author's table shows that the increase in section modulus is roughly proportional to the increase in depth. There is thus obtained a 50 % added bending resistance with no increase in weight.

The disadvantages are equally obvious — the added fabrication costs due to the flame cutting and welding and the decreased shear resistance and tendency to buckling due to the weakened web.

Regarding the first point the author states that experience in Britain indicates that the saving in weight may be taken to range from 11 % to 47 % and the *net money saving* is about half of this.

It is agreed that the castellated beam is especially adapted to the case where a light load is to be carried over a long span. It is not suitable for short beams where the shear effect is critical nor for the case where heavy load concentration must be carried.

It would appear that the stress condition in a castellated beam would be so complex as to defy mathematical analysis. In view of this the United Steel Structural Company of which Mr. SAUNDERS is a Director, instituted a series of full scale tests on typical beams, the tests including an extensive survey of the stress field as well as loading to failure.

The author does not discuss the test results in detail, indicating that the program is continuing, but it is stated that in all beams so far tested, no shearing failure intervened until the load reached a value of 3-1/2 times that which would cause a bending stress of 10 tons per square inch in the flange. It would thus appear that in spite of the perforated web, the castellated beam has ample shearing strength.

The author refers to a photo-elastic study of the stress patterns in a castellated model made by the Civil Engineering Department of the University of Glasgow but these results are not discussed.

The paper concludes with the description of some ten or twelve construction projects on which castellated beams were used. These would indicate that this structural form has achieved considerable popularity in Great Britain — as might be expected if a money saving of 6 % to 24 % can be achieved.

The author notes that the construction has been used to some extent in Europe; so far as the present writer knows is has not so far found application in the United States.

IVd - (1) Paper by Dr. - Ing. WALTER WOLF entitled *«Maintenance of steel structures»*. This paper is devoted primarily to the subject of protection of iron and steel structures against corrosion and it presents a very thorough survey of the field.

The author begins by noting that the corrosion problem cannot be solved by removing the cause — always the most desirable method when possible. But the causes of the corrosion of metals — moisture and gasses — are unavoidable concomitants of our way of life and must be accepted. A table is presented showing the remarkable variation in the rate of corrosion of unprotected iron and steel — this ranges from 5 to 1000 gr./mm.

Three methods of protection are discussed — alloying (which is not recommended except in special cases), painting and coating with protective metal (e. g. zinc or aluminum).

Great stress is placed on thorough preparation of the surface before paint or metal coating is applied. The various methods of preparation — hand-cleaning, sand blasting, flame cleaning, etc. — are discussed at some length. The complete removal of mill scale is recommended in all cases.

In the matter of painting it is noted that there is no single paint that can be said to be best in all cases. Generally speaking the author favors the old, well-tried red lead as a prime coat and mentions several different combinations for the outer coats.

For locations where atmospheric conditions are normal and free from industrial impurities one prime coat and one finish coat are recommended. For a marine climate or an industrial location it is considered desirable to apply at least 2 prime coats and two outer coats.

A brief discussion of metal coatings (applied by spray, bath or electrolytically) is given. When properly applied to a well prepared surface excellent results are obtained. One of the protective coverings that can be obtained consists of a thin zinc coat sprayed on the steel surface (which must be cleaned to the «white metal»), this surface roughened by application of phosphate and then given the normally required coats of paint. This process is relatively costly but gives very long-lasting protection and hence is especially adapted for hydraulic structures and others where inspection and re-painting are especially difficult.

In regard to painting, the paper emphasizes the economic advantage of using only the best materials in the original paint job. The cost of materials in only 20 % to 25 % of the total cost of applying a coat of paint; if by using high-grade materials the paint lasts 3 or 4 times as long as would a cheap job, the money is well spent.

It is noted that structural steel is ofen placed in an unfavorable competitive position in the construction market (compared, say, to reinforced concrete) due to the widely held belief that, because of the requirement for frequent repainting, the maintenance cost for steel is always much higher.

It is conceded that where the original paint job is a poor one, caused either by careless workmanship or an effort to save on materials cost or both, the maintenance cost may indeed be very high. However, it is the author's opinion — and he cites a number of distinguished authorities in support of this — that if the original painting is firstrate and is followed by careful periodic inspection, the maintenance cost of steel is no higher than that of reinforced concrete.

The paper concludes with a discussion of the role that can be played by the designer in promoting lower maintenance costs by avoiding sharp corners, pockets and other rust-inducing details. Modern type box sections are, in this respect, obviously much superior to U- and T-shapes and a welded hollow box section is a nearly ideal form for reducing the likelihood of corrosion. Several examples are shown.

(2) Paper by Messrs. A. van AALST and G. J. DOLPHIJN, entitled — «*Maintenance of steel construction*».

While this paper contains some discussion of the corrosion problem in general, it is principally concerned with rust protection of hydraulic structures. Three types of protection are discussed:

a. *Paint*

b. *Bituminous Covering*
   1. Asphalt Bitumen
   2. Tar Bitumen

c. *Metal Coating*
   1. Zinc
   2. Aluminum

The authors agree that paint on underwater structures has a very limited life and is not recommended.

Asphaltic Bitumen gives excellent results and the authors consider tar bitumen, when certain admixtures (which are described) are provided, can be made quite satisfactory.

Zinc coating obtained by immersion in a hot zinc bath (galvanizing) furnishes good protection; application of zinc by spray or by use of paint containing a high percentage of zinc powder is not so highly recommended.

Aluminum, applied by spray gives very good protection for hydraulic structures, its principal disadvantage being its high cost.

The paper closes with a discussion of the corrosion problem in reinforced concrete in which the authors present their own theory of the chemical interaction between the steel and the concrete. This is highly technical and difficult to summarize.

In the matter of rust prevention (or the reduction of corrosion) the authors make the usual recommendation that new structures should provide ample cover for the steel and be designed to minimize cracking as far as possible.

For protection of existing structures where the steel has become exposed some type of bitumen covering is recommended.

(3) Paper by M. F. PALMER, M. I. C. E., M. I. Struct. E. entitled — «*Repairs and maintenance of steel structures*».

This paper covers a variety of topics.

In the recently conducted program of repairs on the Tower Bridge, a limited use was made of a novel and ingenious method of repairing rusted rivet heads by thoroughly cleaning the surrounding space and then welding the heads to the plate. This would appear to be a simpler and cheaper process than cutting out the old rivets and replacing them with rivets of bolts. As the author notes, this is often a difficult and costly operation since, particularly in the case of punched holes, it is seldom possible to drive out the old rivets — they must be drilled out.

Some tests made indicated that a repair of this type provides the full strength of the original connection.

The paper discusses some of the faults in design of structures which lead to serious maintenance problems — inaccessibility of details, water pockets, unprotected roller nests, inadequate expansion joints, etc.

The paper also devotes considerable space to the subject of cleaning and painting of steel work. Wire brushing, grit blasting, phosphating, flame cleaning and pickling are discussed, as are painting, metal spraying and galvanizing.

On these topics the author's views appear, generally speaking, to be quite in line with those of Dr. WOLF and Messrs. van AALST and DOLPHIJN.

Mr. PALMER also fully agrees with Dr. WOLF on the great superiority of welded construction from the standpoint of maintenance.

SUMMARY

Theme IV does not present a single, closely integrated subject and the papers presented are so diverse in character that it is difficult to draw general conclusions applying to the field as a whole.

Considering the three sub-divisions:

IVb – Dr. ROCKEY has presented a new set of design formulas for stiffened webs of aluminum plate girders. The formulas reflect aesthetic as well as strength considerations.

The results of his extensive test program reinforced the design principle, widely known but as yet not generally reflected in specifications, that rational «safe unit stresses» can only be determined by considering their relation to the ultimate carrying capacity of the structure as a whole.

Dr. ROCKEY'S Table I shows that for the 8 cases reported, the ultimate load was from 5 to 8 times the nominal critical buckling load and about 3 times the load producing initial yield.

IVc – (1) The paper by Messrs. BORGES and LIMA indicates that in spite of the enormous progress that has been made in perfecting the *theory* of structures, there is still something to be learned from testing models to destruction.

(2) Probably every designing engineer has at times chafed at the limitations in the size of rolled sections — wishing he might get a deeper beam without too much added weight. Mr. SAUNDERS' paper presents a novel and clever method of approximating this by cutting the web so as to provide two tooth-like sections and shifting and welding these to produce an open webbed girder, stretched out in depth but of the same weight.

IVd – The three papers on maintenance of steel structures present a thorough treatment of the problem of protection against corrosion for steel structures of all types and in varied locations. Mr. PALMER also presents some interesting data on bridge repairs.

ZUSAMMENFASSUNG

Thema IV stellt nicht einen einzelnen, zusammenhängenden Gegenstand dar, und die vorliegenden Berichte sind so verschiedenen Charakters, dass es schwierig ist, allgemeine Schlüsse über das Thema als Ganzes zu ziehen.

Betrachten wir die drei Unterabschnitte:

IVb – Dr. ROCKEY hat neue Bemessungsformeln für versteifte Stehbleche von Blechträgern aus Aluminium aufgestellt. Die Formeln berücksichtigen sowohl aesthetische als auch festigkeitstechnische Ueberlegungen.

Die Ergebnisse seines ausgedehnten Versuchsprogramms bestätigen das bereits bekannte, aber noch nicht allgemein bis ins Einzelne ausgearbeitete Bemessungsprinzip, nämlich dass vernünftige zulässige Spannungen nur angegeben werden können, wenn man ihre Beziehungen zur Höchsttragfähigkeit des Bauwerks als Ganzes berücksichtigt.

Dr. ROCKEYS Tafel I zeigt, dass für die acht genannten Fälle die Höchstlast fünf bis acht Mal so gross war wie die zulässige kritische Beullast und ungefähr drei Mal so gross wie die Last welche den Fliessbeginn hervorruft.

IVc – (1) Der Bericht der Herren BORGES und LIMA zeigt, dass man trotz des enormen Fortschrittes in der Vervollkommnung der Konstruktions*theorie* aus Bruchversuchen an Modellen immer noch etwas lernen kann.

(2) Wahrscheinlich hat sich jeder Konstrukteur schon hie und da über die Begrenzung der Grösse von Walzprofilen aufgeregt und gewünscht, er könne einen grösseren Träger finden ohne das Gewicht

erheblich zu vergrössern. Der Bericht von Mr. SAUNDERS zeigt eine neue und geschickte Methode, dieses Ziel zu erreichen, indem man das Stehblech so zerschneidet, dass zwei sägeblattförmige Abschnitte entstehen, und diese so zusammensetzt und verschweisst, dass man einen Träger mit Oeffnungen im Stehblech erhält, der eine grössere Höhe, aber das gleiche Gewicht hat.

IVd – Die drei Berichte über den Unterhalt von Stahlkonstruktionen stellen eine umfassende Untersuchung des Problems Korrosionsschutz für Stahlbauten aller Arten und in verschiedenen Lagen dar Mr. PALMER gibt auch einige interressante Angaben über Brückenreparaturen.

RESUMO

O tema IV não apresenta um assunto único e bem delimitado e as contribuições apresentadas são de características tão diversas que se torna difícil tirar conclusões gerais aplicáveis ao conjunto.

Considerando as três sub-divisões:

IVb – O Dr. ROCKEY apresentou uma nova série de fórmulas para o cálculo das almas reforçadas de vigas de chapa de alumínio. As fórmulas refletem considerações estéticas a par das de resistência.

Os resultados do seu extenso programa de ensaios vêm confirmar o princípio de cálculo já conhecido, mas que até agora não se tem geralmente reflectido nos cadernos de encargos, de que as «tensões unitárias de segurança» só podem ser determinadas racionalmente considerando-as em relação à capacidade de carga final da estrutura completa.

A tabela I da contribuição do Dr. ROCKEY mostra que nos oito casos examinados a carga era de cinco a oito vezes maior que a carga crítica nominal de encurvatura e três vezes maior que a carga que produzia a deformação inicial.

IVc – (1) A contribuição dos Srs. BORGES e LIMA mostra que, apesar dos progressos enormes feitos no aperfeiçoamento da *teoria* das estruturas, ainda há algo a aprender em ensaios de modelos à rotura.

(2) Todo o Engenheiro de estudos já reagiu certamente contra as dimensões limitadas dos perfis laminados e desejou ter à sua disposição vigas mais altas sem acréscimo exagerado de peso. A contribuição do Sr. SAUNDERS apresenta um método original e interessante, para satisfazer esse desejo, recortando a alma de um perfilado em forma de dentes, deslocando e soldando as peças assim obtidas de modo a ter uma viga de alma aberta, de altura maior e de peso igual.

IVd – As três contribuições referentes à conservação das estruturas metálicas tratam de maneira muito completa o problema da protecção contra a corrosão das estruturas de todos os tipos e em vários locais. O Sr. PALMER apresenta igualmente alguns dados interessantes sobre a reparação das pontes.

RÉSUMÉ

Le thème IV ne concerne pas un sujet unique et bien déterminé, et les contributions présentées ont un caractère tellement divers qu'il est difficile d'en tirer des conclusions générales pouvant s'appliquer à leur ensemble.

En considérant les trois subdivisions:

IVb – Le Dr. ROCKEY a présenté une nouvelle série de formules pour le calcul des âmes renforcées de poutres en tôle d'aluminium. Les formules se fondent sur des considérations tant esthétiques que de résistance.

Les résultats de son vaste programme d'essais viennent confirmer le principe de calcul bien connu, mais qui n'apparaît guère encore dans les cahiers des charges, de ce que les «contraintes unitaires de sécurité» ne peuvent être déterminées rationnellement qu'en les considérant par rapport à la capacité de charge finale de l'ensemble de la structure.

Le tableau I de la contribution du Dr. ROCKEY montre que pour les huit cas éxaminés, la charge finale était cinq à huit fois plus grande que la charge nominale de voilement et environ trois fois plus grande que la charge produisant la déformation initiale.

IVc – (1) L'article de MM. BORGES et LIMA montre que malgré les progrès énormes faits dans le perfectionnement de la *théorie* des structures, il y a encore beaucoup à apprendre par des essais à la rupture sur modèle.

(2) Il est probable que tout ingénieur d'étude s'est une fois ou l'autre heurté aux dimensions limitées des profils laminés, souhaitant disposer d'une section de hauteur plus grande sans augmentation de poids exagerée. L'artcle de M. SAUNDERS présente une méthode originale et intéressante de satisfaire à ce désir en découpant l'âme d'un profilé en créneaux, en déplaçant et soudant les deux pièces ainsi obtenues de manière à avoir une poutre à âme ajourée, plus haute et de poids égal.

IVd – Les trois articles concernant l'entretien des structures métalliques traitent d'une manière très complète le problème de la protection contre la corrosion des structures de tous types dans les lieux les plus divers. M. PALMER présente également quelques renseignements intéressants sur la réparation des ponts.

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