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SUGGESTIONS

FOLGERUNGEN UND ANREGUNGEN

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Theme I.

Importance of the Ductiliy of Steel for Calculating and Dimensioning Steel Structural Work, especially when Statically Indeterminate.

1) In order to assess the safety of a structure or structural member of steel it is necessary to take into account the conditions of equilibrium and strain under increasing load after the plastic state has already partly been attained. The shapes of cross section of bars and girders have an effect on the occurrence of this plastic state and, therefore, on the carrying capacity and safety. The usual hypothesis of uniform transference of stress through the constituent parts of a steel structure (whether riveted or welded) is fulfilled by reason of the ductility of the steel.

The classical theory of plasticity, when applied to investigations of stable and unstable equilibrium in steel structures, assumes that the occurrence of the plastic condition (flow) depends on local conditions of stress. A newer hypothesis rests on the view that the phenomenon of flow depends on the configuration of the field of stress and is, therefore, manifested in a series of discontinuous jumps. Experiments recently carried out on bending specimens and on eyebars indicate that the large increase in the yield point — previously noted in cases where the stresses are not uniform — is to be attributed to differences in the interpretation of the experimental results. It has been found that the upper yield point of the steel is an important property of the material and one which cannot be accurately ascertained in the tensile test. In bending, an upper yield point always occurs quite independently of the cross section. The occurrence of the flow by a series of jumps is attributed to the effect of this upper yield point. Future developments of the theory of plasticity must take account of the conditions of stress and strain in a member within the plastic range, and supporters of the new conception of the condition of flow no longer look upon the maximum stress as being a decisive criterion. Further experiments are contemplated with a view to clearing up the uncertainties which remain.

2) Both the classical theory of plasticity and the new condition of flow have been adopted as a basis for the solution of problems of stability (under eccentric pressure). It is found that about equally simple results are obtained whichever of these methods is applied. The new criterion of flow leads to results which agree very well with those obtained in experiments.

3) The case of a load increasing from zero to a maximum value appears to have been cleared up so far as continuous girders of uniform cross section are concerned. The principles deduced from the experiments are to be further investigated by reference to the two alternative criteria of flow. For practical purposes a simple method of arriving at the effective carrying capacity is desi-

rable. Here, however, it is necessary to take account of the final upper limit to which plastic strain extends.

4) As yet no experiments have been carried out under varying loads. The theoretical principles still require to be checked by reference to the new knowledge acquired.

5) In plate web girders free from large notches, it has been shown by fatigue tests that the permanent deformations arising where the girder is continuous over a number of equal spans tend towards a fixed limit, even when the number of repetitions of load is made very large (700,000). Further experiments are in hand, and until these are completed the application of the "equilibrium load method" to the design of dynamically stressed structures (subject to fatigue failure) cannot be recommended.

6) The investigations already carried out make it possible to ascertain the effect of sinking of the supports, which in most cases appears to be inconsiderable.

7) In the case hitherto examined of statically indeterminate framed structures, the method of calculation is subject to a qualification when it is applied to the dimensioning of compression bars which cannot be utilised for equalising the moments. In more general cases, however, the assumptions that may properly be made on this point call for further careful examination.

8) It may be stated, in summary, that in many cases the ductility of the steel results in an increase in the safety of statically indeterminate structures by comparison with those that are statically determinate. The increased carrying capacity which theory justifies and experiment confirms can be turned to account economically by means of the methods of calculation now available for application to building frames. In a few cases the equalisation of moment brought about by the automatic "cold working" effect has been reflected in official regulations. The economic advantages are most apparent in the case of structures of uniform cross section throughout their legth, and less so in structures where the cross section has been adapted according to the variation in forces (such as moments).

Theme II.

Stresses and the degree of safety in reinforced Concrete from the designer's point of view.

1) In the *calculation of reinforced concrete sections subjected to bending* a distinction should be drawn between the first case, corresponding to a lightly reinforced section wherein failure is governed by the yield point of the steel, and the second case in which it is governed by the compressive strength of the concrete. As regards the first case it is possible to calculate the lever arm of the internal forces, and hence the resisting moment, by reference either to Navier's theory of bending as applied to the compound section when cracking is about to take place, or by reference solely to conditions of equilibrium at the moment when failure is imminent. The two methods of calculation give values of resisting moments which differ little from one another, so that no occasion arises to modify the methods of calculation hitherto in use.

In the second case, where failure is determined by the compressive strength of the concrete, it is not possible to calculate the resisting moments by reference to the conditions of equilibrium alone. Here the usual method of calculation does not give the correct factor of safety, and it would be desirable to adopt a new method of calculation ensuring better utilisation of the material and, at the same time, enabling the limiting amount of reinforcement which separates the two cases from one another to be calculated. This will as far as possible avoid the need for compression steel and for haunching under the ends of the beam, and will thus improve the design.

In the case of bending combined with axial loading the present usual method of calculation does not give a correct idea of the conditions in regard to the factor of safety; it is proposed that the best method of calculation should be worked out on the basis of experiments and on the lines of the Norwegian draft regulations for reinforced concrete.

At the Congress expression was given to the view that the usual methods of calculation for bending fail to afford a correct indication of the factor of safety, and that it would be a problem of the future to develop a new method, with a view to more complete utilisation of material, taking account of the plastic behaviour of the concrete and of shrinkage.

2) *The resistance of unreinforced concrete against frequently repeated loading* (varying between zero and a fixed upper limit) in compression, tension and bending may be taken as equal to approximately half the strength as ascertained in the static test. In the case of reinforced concrete members exposed to frequently repeated loads attention must be given to the perfect anchorage of the reinforcing bars, and to the ample curvature of these bars at the places where they are bent up.

3) *The tensile strength of concrete* is the second most important characteristic of the material, the first being the cube compressive strength. Like the tensile strength it depends primarily on the cement content, the granulation and the water-cement ratio. Tensile tests of concrete members afford no satisfactory criterion, but bending tests on concrete beams have given good results.

4) It is recommended that the views and suggestions put forward by M. *Freyssinet on improvements in concrete* should be examined from their physical aspects with a view to their utilisation in practice. The basic principle of the method consists in reducing or completely eliminating the tensile stresses in the concrete not only for bending but also for shear, as may be done by pre-stressing the reinforcement to a sufficiently high degree. By compressing and heating the concrete it is possible to give it a high strength in a few hours. It is recommended that the properties possessed by a concrete made in this way should be studied.

5) The use of *high tensile structural steel* in reinforced concrete work has fulfilled all expectations. The advantages consist in the permissible stress for the steel being increased up to 1800 kg/cm^2 = 25,602 lbs./sq. in. (or in exceptional cases to as much as 2200 kg/cm^2 = 31,291 lbs./sq. in. according to the elastic limit of the steel and the quality of the concrete. T-beams subject mainly to stationary loads, reinforced with St. 52 with a permissible steel stress of 1800 kg/cm^2 = 26,000 lbs./sq., in. and having a correspondingly increased cube strength in the concrete, exhibit the same degree of safety against cracking as if reinforced with St. 37 at 1200 kg/cm^2 = 17,068 lbs./sq. in. Under moving loads slabs of rectangular cross section are to be preferred to T-beams, on account of their greater safety against cracking.

6) It is recommended that in the construction of floors, water tanks and similar building structures, *temporary expansion joints* should be provided and left open during the period of construction for at least several weeks, and subsequently concreted in. Apart from these it is desirable to provide permanent expansion joints for the purpose of permanently separating the constituent parts of the structure and allowing freedom of relative movement of the latter.

Theme III.

Practical Questions in Connection with Welded Steel Structures.

1) Since the time of the Paris Congress electric welding has made great progress in many countries and a large number of welded railway and road bridges have been constructed. In several countries official regulations on welding are now in force.

2) Experience has shown that low carbon structural steel is a perfectly suitable material for welding; neither is there any doubt as to the suitability of high tensile steels provided the composition of the alloy is known to be such that welding will not make it brittle and liable to crack, and provided that the electrodes are suitably adapted to the composition of the steel to be welded.

3) The types of structure designed with welded connections are pleasing in their proportions, and lend themselves well to the aesthetic development of design.

4) As a rule welded structures are lighter than riveted. Complete structural members such as heavily loaded columns, frames, etc. can be very simply carried out in welded design. The use of welding also offers great advantages in the strengthening of existing steel structures.

5) It may be stated in general that welding entails great care in workshop operations followed by continuous supervision on the site. The quality of welded work depends greatly on the skill of the welder, and calls, for continuous training and supervision of the workmen engaged. A great deal of experience is necessary in order to minimise shrinkage stresses, and this is particularly true in regard to site joints.

6) Laboratory fatigue experiments have shown that butt welds are superior to fillet welds in resisting dynamic stresses of large amplitude at right angles to the seam. Both laboratory experiments and experience in practice have further shown the fatigue strength of welded butt seams, properly carried out, to be at least as great as that of the usual riveted connections. I-beams may be built up in different ways by the butt welding of the web and flange plates, and their fatigue strength is practically equal to that of rolled joists.

7) The fatigue strength of butt welded seams is considerably increased if the root of the seam is re-welded after removing the slag, etc., and if a gradual transition in the seam from the parent metal to the weld is ensured.

The fatigue strength of end fillet seams, and at the ends of side fillet seams, is considerably less than that of continuous fillets. This implies that at the places affected the permissible stress in the parent metal should be reduced. In structures exposed to dynamic stresses intermittent seams and slot welds should be avoided. In the case of fillet seams it is very important that good penetration at the root should be ensured, and for this reason it is recommended that in forming such seams a preliminary run should be made with a welding rod of 3 to 4 mm diameter = abt. $\frac{1''}{8}$ to $\frac{5''}{32}$. The fatigue strength of end fillet seams and at the beginning of side fillets can be considerably increased by a gradual transition from the parent metal to the weld.

8) The heat produced in welding gives rise to shrinkage stresses which may become considerable if the work is unable to follow the movement due to shrinkage. In view of the plastic behaviour of the material these thermal stresses are usually of no significance for the safety of the structure. Extensive experiments on the fatigue bending strength of welded girders have shown that the high shrinkage stresses are not dangerous even in the longitudinal seams of the structures. The measures which may be taken for avoiding shrinkage stresses are the adoption of small cross sections of seam, the supporting of the parts to be welded in such a way that they can move and follow the shrinkage, and the limitation of the heat input per unit of time. By suitably designing the structure and by paying special attention to the sequence of the welding operations, the shrinkage stresses can be kept low.

9) In plate web girders it is preferable to form the flanges of thick plates rather than of several layers of thin plates.

10) It is desirable that important butt welds should be examined by X-ray, and that sample point tests should be made in longitudinal beams. In the case of thick butt welds it is desirable that the X-raying should be done when only a portion of the welding gap has been filled, in view of the fact that shrinkage cracks are particularly liable to arise in the initial runs. The magnetoscopic method, also, is well adapted for detecting cracks close to the surface. In certain cases mechanical methods of testing may be used with advantage.

Theme IV.

New views concerning calculation and construction of bridges and structural work in reinforced concrete.

1) Since the Paris Congress of 1932 methods for the calculation of walled structures have been further developed. Solutions in accordance with the membrane theory are now available in all but a few cases. In the case of shell structures, where no direct solution by means of differential equations is possible a sufficiently accurate solution can usually be obtained by means of equations in finite differences. The problem of shells becomes considerably more difficult when bending moments are present, especially where these bending moments are not due to constraint around the edges but are necessary in order to satisfy the conditions of equilibrium. This is the case above all in freely supported cylindrical shells of simple curvature, whereas in the case of shells with compound curvature only tensile stresses are present as a rule. From the knowledge now available it is possible to calculate exactly the bending moments in these cylindrical shells not only under surface loads but also under a linear distribution of load or under isolated loads, whether for circular or any other forms of cylinder, but the calculation is laborious. Here, as in the case of the simple problem of slabs, there is a need for sufficiently accurate approximate solutions checked against rigorously calculated examples. In the construction of long span shells the problem of safety against buckling becomes of great importance. For the most important kinds of shell — particularly the circular cylindrical shell — this problem has already been solved, and can be treated with relatively little mathematical labour. In determining the safety against buckling, especially in the case of shells with simple curvature (cylindrical shells), deformation must be taken into account, as this plays a part which may be very considerable in the case of thin shells owing to the creep of the concrete.

2) An increase in the span of arch bridges is dependent on careful study of the shape of the arch axis, the variation in the resisting moment and the permissible stresses. The best possible equalisation of moment must be sought and tensile stresses avoided, account being taken of elastic and permanent strains in the arch, the abutments and the foundation. For this purpose it is necessary to know the modulus of elasticity of the concrete as a function of time and of the conditions under which the arch is to be constructed. In arches of box section special attention must be paid to the unfavourable conditions of stress resulting from the division of the arch into two separate slabs.

Progress in bridge construction is further dependent on the possibility of light forms of centreing which will remain true to shape over considerable spans. The method, which has been adopted with success in practice, wherein the centreing is loaded with only a portion of the weight of the arch, gives rise to conditions of strain in the latter calling for further elucidation in order that the degree of safety may be more exactly determined.

3) In beam bridges the adoption of pre-stressed reinforcement opens up a whole range of new possibilities, since in this way much greater spans can be obtained than in existing bridges while at the same time the dead load may be greatly reduced. Moreover it becomes possible to design beam bridges wherein little or no bending tensile stress will arise, even under unfavourable conditions of live load, so that the risk of dangerous cracks is avoided. By this method of design a simply supported beam can be designed with solid webs up to 80 m [262′ 6″] in span, simply supported beams with open webs up to 100 m [328′ 1″] span, and continuous beam bridges up to 150 m [492′ 2″] span.

Particularly favourable conditions may be obtained if the pre-stressed bars are so arranged that only concentric compressive forces will arise in the beam under dead load. The first step in the realisation of reinforced concrete bridges by these new methods has already been taken, in that a bridge of approximately 70 m [229′ 8″] span is now under construction, and the experience thus gained will be available for designing bridges of still greater span.

In these pre-stressed bridges great importance attaches to precise knowledge of the modulus of elasticity of the concrete, in order that the effects of creep and shrinkage may be eliminated.

If advantage is taken of this method, arranging the stirrups in such a way that the dead loading will give rise mainly to concentric compressive stresses alone and that no plastic bending will occur, the stresses in these stirrups may be correctly determined even if the modulus of elasticity is not exactly known. Otherwise the stresses in the pre-stressed bars in question must be measured with extensometers or by other means.

Theme V.

Theory and research work on details for steel structures of welded and riveted construction.

Since the Paris Congress numerous theoretical and experimental questions regarding details of riveted and welded steel structures have been dealt with; for instance important mathematical investigations have been published on various problems of strength and stability (stiffening of the webs of plate web girders; bending, torsion and buckling of thin walled members, rigid frame intersections; stresses in frame corners, etc.). Interesting researches have been carried out on the exact calculation of trusses, the applications of shells in steel construction, the calculation of secondary stresses, the fatigue resistance of welded connections, etc. These investigations enable a useful opinion to be formed of the degree of accuracy which attends the usual methods of calculation. They also afford a check on the correctness of theory when exact measurements can be made on completed structures. Great progress has been made in methods of experiment depending on measurements on models and on completed work, these being especially useful in application to important works or to those structural members which are frequently repeated in constructional design. Measuring methods and apparatus have been improved to a point which makes it possible to use them in a large range of cases. Such measurements should be developed to the greatest possible extent, in order to furnish a basis for methods of calculation with a view to improved understanding of the conditions of stress arising in structures, and finally with a view to promoting the economical and safe design of steel structures.

Theme VI.

Plain and reinforced Concrete for hydraulic Structures.

1) *The calculation of arched dams* is usually based on the assumption that the structure is divided into two systems of components, namely horizontal arches and vertical walls. In some cases it may be desirable to take account of the deformability of the ground under the foundation. A more exact calculation has been attempted by assuming the arched dam to consist of elastic shells with a steeply varying moment of inertia, but this is still in the domain of theory and it has not been found possible to apply it in practice. The strains which in fact arise in arched dams depend greatly on the method of construction and on the measures adopted for applying the initial pressure to the construction joints. In cases where the reservoir is filled with water progressively while the dam is being built it is desirable to investigate the effect of the water pressure at different stages of progress.

2) In the *construction of dams and other massive works* the concrete must be not only strong and dense, but above all workable. In such work the use of a wet very plastic concrete has generally superseded that of poured or rammed concrete. Experience on work exposed to unfavourable climatic conditions has shown that a concrete offering resistance to frost is obtained only when the admixture of cement is at least 250 kg/m^3 [421 lbs./cu. y.]. The concreting of large masses calls for special measures in order to avoid the formation of cracks due to cooling, and these precautions become more important in proportion as the speed of construction is increased. The simplest precaution consists of dividing the wall into blocks of relatively small size. In very large works measures for artificial cooling are to be recommended. The amount of heat released in the hardening process may be reduced by a suitable choice of cement or of hydraulic admixtures. In large dams (at least in gravity dams) a system of inspection shafts and tunnels must be provided in order to allow of observation being kept on seepage.

3) The observations made above regarding the application of concrete in the building of dams apply also, *mutatis mutandis*, to hydraulic engineering work for the purposes of navigation (dry docks, locks, etc.).

4) Reinforced concrete pipe lines have been made in very large diameters to resist heavy internal pressures, special measures being taken to reduce the tensile stresses in the concrete. The construction of a hooped pipe of 4.4 m [14′ 6″] internal diameter, as described in the Preliminary Publication, represents a new and promising application of the device of pre-stressing. The use of pre-stressed cables has also been successfully applied to the strengthening of a gravity dam.

Theme VII a.

Application of steel in bridge and structural engineering.

1) The reports and contributions to the discussion at the Congress reflect very notable developments during the last few years in the application of steel to bridges and other structural work. It is also apparent that much greater importance than hitherto is now being attached to the aesthetic aspects of structural work, and in many ways this has given a new impulse to the development of steel construction. A series of handsome steel bridges built during the last few years demonstrate the possibility of reconciling structural necessities with aesthetic requirements.

The attractive designs which have been made for halls, exhibition buildings, etc. represent important developments in steel construction, whether regarded from the point of view of the framework or that of the concordance of steel with glass, or any other combination.

2) There can be no doubt that the new forms developed from the structural and economic exigencies of design have had stimulating repercussions on theory. Thus the problem of the stability of the plate web girder may be looked upon as more or less solved, and very notable progress has also been attained in the theoretical and practical development of framed construction.

3) During recent years a great impulse to the development of steel construction has been given by the growth in the use of welding which offers great advantages from the technical, economic as well as aesthetic points of wiew. In general, steel structures when welded are more readily adapted to aesthetic considerations, and give the impression of a more homogeneous beauty. The development of the art of welding will still further encourage the use of steel once a solution has been reached to many outstanding problems which are now being studied by laboratory and full-scale tests.

4) An interesting new development is to be recorded in the application of steel to self-supporting systems. The theoretical principles of the resistance and stability of these systems are now understood and can be applied with great advantage in the roofing of halls and hangars. Light weight floors for road bridges also take this form, and welding provides a special stimulus to their development. Welding and light weight design are considerably extending the competitive power of steelwork in the field of small bridge construction.

In assessing the economy of new forms of design it must not be overlooked that changes in the technique of construction, due to the adoption of this new method, may be of quite decisive importance.

5) The results of fatigue experiments, so far as they concern the dimensioning of structural members, exposed to alternating or pulsating loads, have shown that the permissible stresses in high tensile steel might be increased when the

permanent limits of stress are high, within the bounds justified by consideration of stability.

The criteria for expressing the results of fatigue tests in practical rules of design still await clarification in the light of further experimental measurements.

6) In structural steel construction, extensive full-sized fire tests on loaded columns provided with different forms of covering have gone far to solve the problem of finding suitable materials for this purpose, and it should now be possible to arrange these in a sequence according to their suitability for fire protection.

7) Finally there must be placed on record an ever increasing development in the combined use of steel and concrete for bridges and building frames. Measurements which have been carried out on structures in service have proved the accuracy of the methods of calculation in use, and have shown that it is possible to realise considerable economy in the construction of bridges by taking account of the co-operation of the steel girders with the reinforced concrete decking slab.

Likewise the combined action of the usual compound form of steel column with a concrete core has been fully confirmed in buckling tests under concentric and eccentric loading, so as to justify an increase in the permissible stress in the steel where special methods of calculation are applied. Another series of tests to examine the effective co-operation of different kinds of covering over steel frameworks are being undertaken.

Theme VII b.

Application of Steel in Hydraulic Construction.

The papers and contributions to the discussion on this question indicate that the importance of steel as a material in hydraulic engineering has notably increased in the last few years. Despite the special peculiarities of the problems which arise in applying steel to hydraulic construction it is expedient to recognise their relationship to steelwork in general, in order that general solutions may be found for certain of the questions.

Among these the problem of corrosion takes a particularly important place. In order that good progress may be made in this field it is necessary that a large range of observations and experience should be covered by collaboration with steelwork engineers. Experience to date discloses, for instance, the welcome fact that the resistance of steel sheet piling to corrosion is greater than was expected at the time of its introduction.

The progress of the fight against damage through corrosion, both on the side of surface treatment and on that of the composition of the material, is no doubt destined to have very favourable repercussions on the development of steelwork applied to hydraulic engineering. It would be desirable that the International Association for Bridge and Structural Engineering should collect observations and data on corrosion from all countries, each individual observation being described as completely as possible, not omitting even those characteristic circumstances of the cases under observation which, so far as our present knowledge goes, may appear to be without significance from the point of view of the phenomena of corrosion.

The technique of welding offers great advantages in the construction both of flat components and of members which need to be rigid against torsion. Water tightness is easily obtainable by the use of welding. Welded hydraulic constructions are often preferable to riveted because of their easier maintenance. The special problems of hydrodynamics and flow which are encountered in hydraulic work call for an intimate collaboration between structural steelwork and hydraulic engineering as taught in the universities.

Theme VIII.

Soil research. (Soil mechanics.)

1) Since the Paris Congress of 1932 research on foundations has made great progress. In addition to an extensive literature in the periodical technical press a number of independent papers dealing with the subject have appeared, offering guidance and information for practical engineers. The methods which have now become established allow, in most cases, the magnitude of the settlement of structures to be estimated in advance. The application of foundation research to practice has recently undergone rapid development. The Congress recommends that the study of foundations should be included in the syllabuses of the technical colleges.

2) The calculation of the maximum load which a foundation surface can carry while remaining in equilibrium is the fundamental question of soil mechanics. The concept of cohesion has been clarified so that the formula for the limiting equilibrium resistance of a foundation slab may be extended to any soil possessing this property. The problem of the carrying capacity of a foundation slab limited on all sides, under the critical condition of equilibrium, has not yet been completely solved.

3) *The distribution of pressure over the ground* may be studied by analogy with the conditions of radiating stresses. *Boussinesq*'s theory with its later extensions has been found very valuable, since when combined with examinations of undisturbed samples of soil it enables the amount of settlement to be predicted. The theory of the compression of layers of clay has been greatly developed quite recently, and can now be applied in practice.

4) *The dynamic investigation of the ground* has been found very valuable in practice. The development of geophysical investigations of the ground give promise of methods which will be important in practice.