# Stresses in girders with broken axis

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# V 6

## Stresses in Girders with Broken Axis.

## Spannungen in Trägern mit geknickter Achse.

## Contraintes dans les poutres à axe brisé.

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1) *Introduction.*

The covering of the platforms of the new station at Florence comprises, as main supporting members, girders which are spaced 6.60 meters apart and the particular form of which is illustrated in diagram I (fig. 1).

All these girders are simply supported at both ends; their length is about 30 meters, with a maximum height of 1.84 meter. The girder has an I-section with a web of 15 mm thickness, and welded-on flanges, 33 cm wide and 20 mm thick, except at the places indicated by a circle on fig. 1, in the zone A B, where the thickness of the flanges has been brought up to 30 mm. Moreover, the web is stiffened by means of ribs, the mean spacing of which is 1.25 meter and which are disposed as is clearly to be seen on the drawings.

All joints in the different parts of the girders have been made by electric welding.

As regards research work on the static behaviour of such girders, the Direction of the Italian Office for Bridges has undertaken a series of experimental researches in collaboration with the Institute of Applied Mechanics for Structures in the Polytechnic School of Milan, directed by Prof. *A. Danusso.*

The study of the elbows at A and B, in which the axis of the girder shows a double and sharp bend, is of particular interest. On this subject, preliminary researches on models have been executed at the Laboratory of the Institute, in order to verify approximately the prevailing conditions of stresses and to obtain informations and verification basis for the calculation and erection of such girders.

Later on and after erection of the structure, extensive researches have been undertaken, as checking, in order to determine finally, on the structure itself and under load, the actual conditions of stresses. The object of these researches was also to provide a comparison between calculated and experimental results as regards both the points above mentioned and any element intervening in the factor of safety of the finished structure.

2) *Tests on models.*

Two series of tests have been completed. The first series has been executed on small plane models, of the form of the middle portion of the girder and

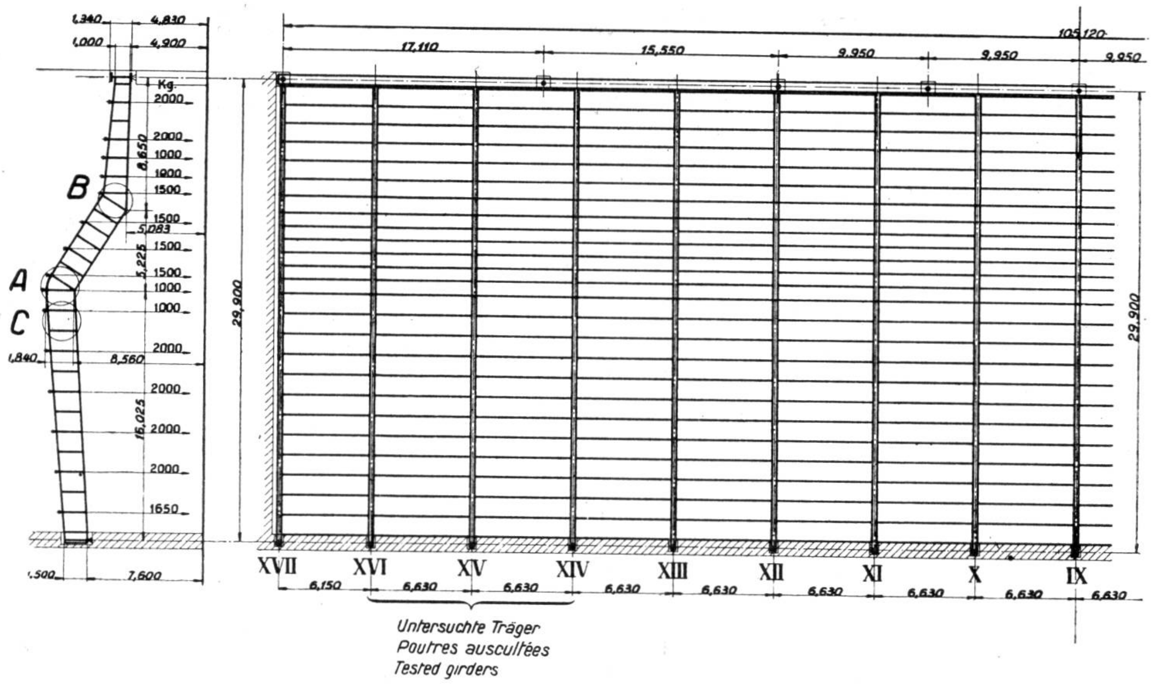


Fig. 1.

made from transparent material (glass and phenolite). These models have been submitted to tests in polarized light, according to the methods of photo-elasticity.

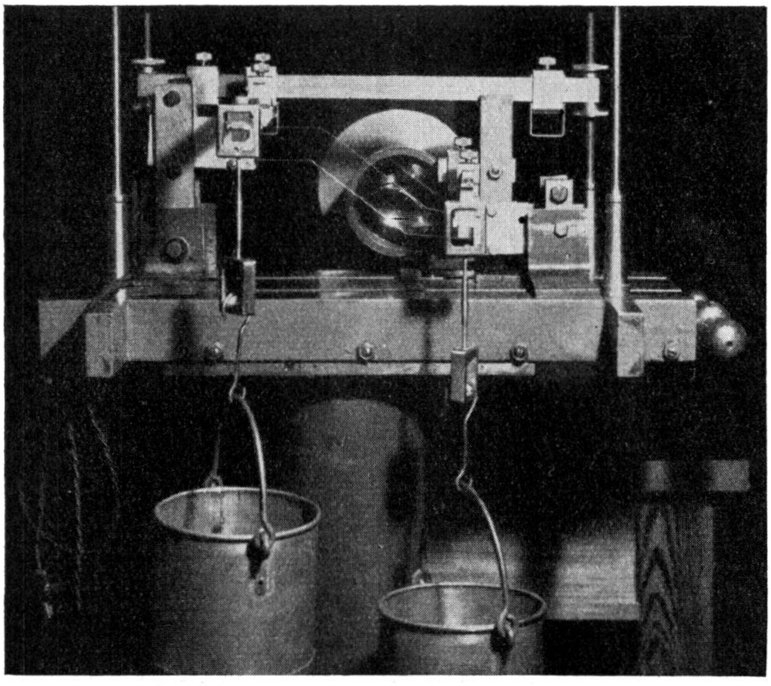

Fig. 2.

The models have been subjected to a constant couple, by means of a device which is illustrated in fig. 2. Fig. 3 represents one of the results obtained and gives the flow of the principal stresses, obtained by examination with monochromatic polarized light.

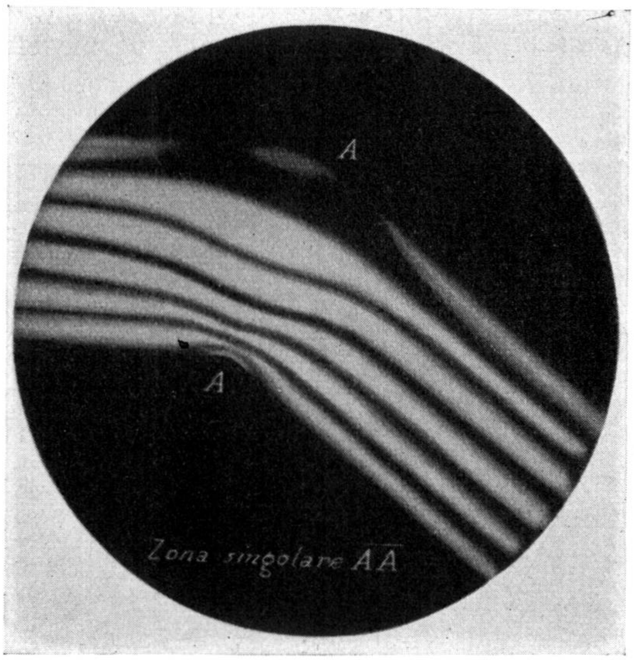


Fig. 3.

The second series of tests was executed in order to approach as much as possible the actual conditions of service, on a reduced steel model, at the scale of 1/5. This model consisted of two beams, assembled, welded and stiffened in the same way as the actual girders themselves. Fig. 4 gives a representation of the whole device, together with the arrangement used for the application of the loads.

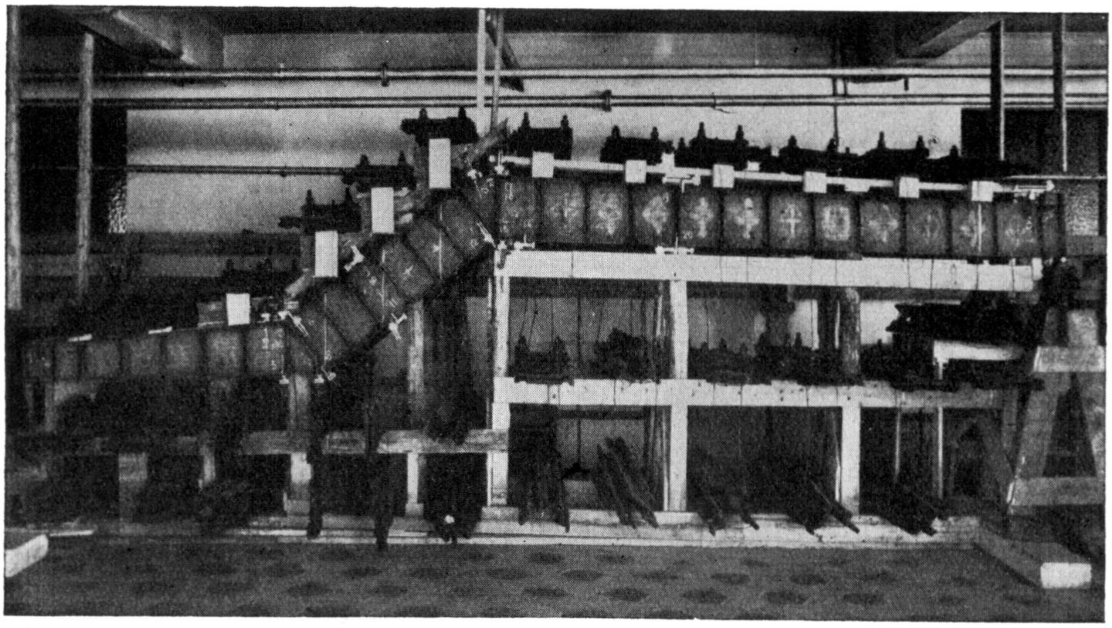

Fig. 4.

In this model, however, and according to the initial study of the scheme of the girders, the flanges had a constant thickness of 5 mm which corresponds to the constant thickness of 20 mm for the flanges of the actual girders. Owing precisely to the results of photo-elastic tests and of the tests on the steel model, the thickness of the flanges in the vicinity of the elbows A and B has been brought to 30 mm, as already indicated above.

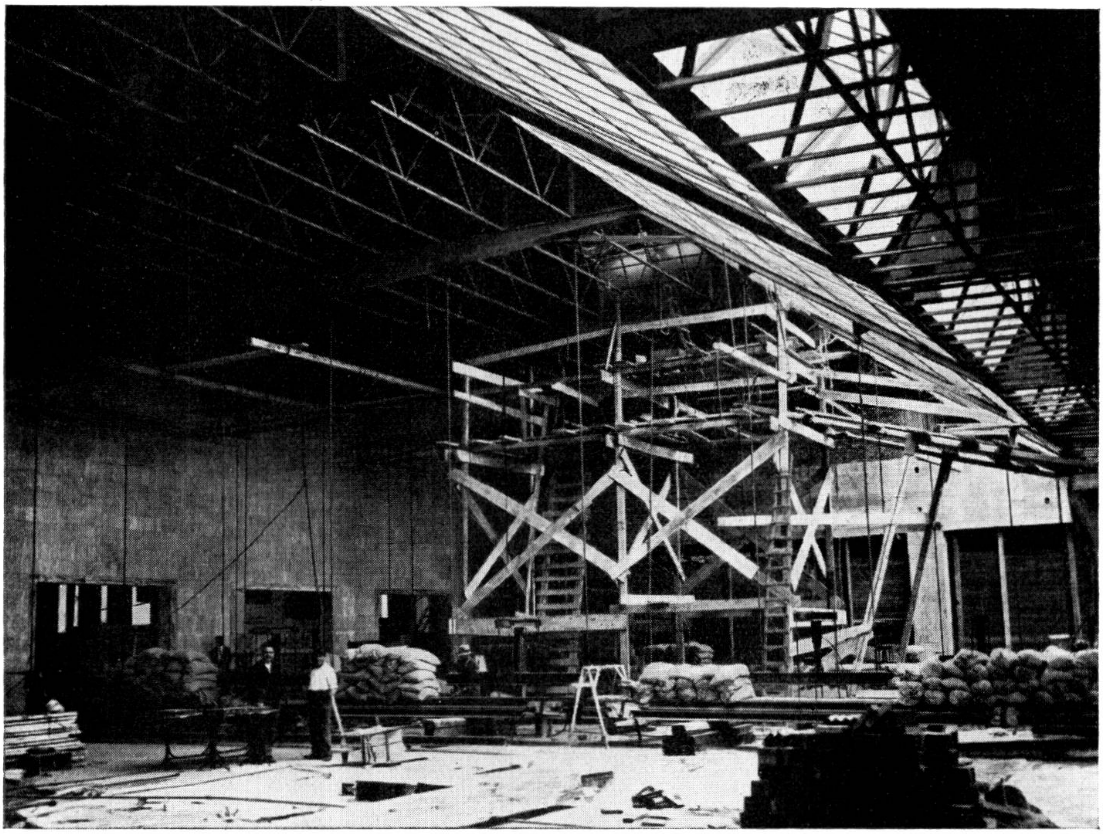

Fig. 5.

3) *Tests on the site.*

These tests have been performed after erection of the girders, purlins and bracing members; the structure was therefore not completed, such members yet failing as were to constitute the roofing itself. Taking into account the weights of these roofing materials and of the accidental loads which had been foreseen in the design, a vertical load of about 750 kg per running meter of girder had to be chosen for testing. For conveniency, this load has been concentrated at a number of points on the girders, as indicated in fig. 1.

The experimental work of research on the actual structure has been limited to one girder, situated as the fifteenth girder from the end of the platform roof. On this girder, the extensometers intended to give the values of the stresses, have been disposed, the modulus of elasticity being known. Taking into account the fact that the neighbouring girders were in a position to share in supporting a portion of the load, owing to the presence of the purlins and to the upper windbracing, it has been considered as convenient to load at the same time the girder under consideration as well as the two neighbouring girders, as represented in fig. 1. Moreover, as a great number of flexometers were available, the measures of deflections have been made not only on the three girders above mentioned, but also on the contiguous girders, in order to allow controlling of how far the influence of the load travelled, as indicated in diagram II (fig. 6).

Taking into account the final object of these tests, it was necessary to repeat the applications of the loads a sufficiently great number of times; it was therefore decided to apply the load to the girders by means of hydraulic presses, reacting against the weight of rails and sacks which were disposed on the ground.

Fig. 5 represents the general arrangement for testing at site. The measuring of actual forces were obtained by readings on manometers ganged in the laboratory. In the same way, the jacks for the girders to be tested had been carefully controlled at the outset.

4) *Instruments used.*

Two classes of instruments were used for these experimental investigations: flexometers and extensometers. The flexometers, supplied by the firm *Mahr*, allowed measuring up to $^2/_{1000}$ millimeter; they were mounted on the floor, on stiff and stable supports. The deflections were transmitted from the girders to the measuring instruments by means of steel wires, stretched by weights. Twenty-two instruments altogether were used in this manner.

The extensometers used were of two types, equally well known: *Huggenberger*'s extensometers with mechanical magnification and direct reading and *Schaefer*'s extensometers, of the electro-acoustical type, with distance reading. Twenty-nine *Huggenberger*'s extensometers and twenty-seven devices of the *Schaefer* type were used. The main characteristic features of these instruments follow from the following table.

| Type of extensometers | Base of measure Minimum in mm | Number of instruments used | Average magnification | Unit deformation per degree |
|---|---|---|---|---|
| Huggenberger | | | | |
| A | 20 | 7 | 1220 | — |
| B | 20 | 16 | 1000 | — |
| C | 100 | 6 | 320 | — |
| Schaefer | | | | |
| D 6 | 150 | 16 | — | $4{,}25 \cdot 10^{-6}$ |
| D 177 | 120 | 7 | — | $3{,}26 \cdot 10^{-6}$ |
| D 156 | 120 | 2 | — | $2{,}10 \cdot 10^{-6}$ |
| D 234 | 20 | 2 | — | $3{,}29 \cdot 10^{-6}$ |

Owing to the high temperature prevailing on the days during which these tests were made, it was preferred to begin with actual testing either in the early morning or late in the evening, in order to be in a position to consider as negligible the influence of temperature. For the same reason, care was taken to reduce the time necessary to a strict minimum. In spite of the great number of instruments employed, the time normally necessary for carrying out the measures could thus be limited, for each loading, to the first twenty minutes.

5) *Results from the flexometers.*

The results thus obtained are given in diagram II (fig. 6). This diagram gives the average results obtained by loading both of one girder (15th girder) and, at the same time, of three contiguous girders.

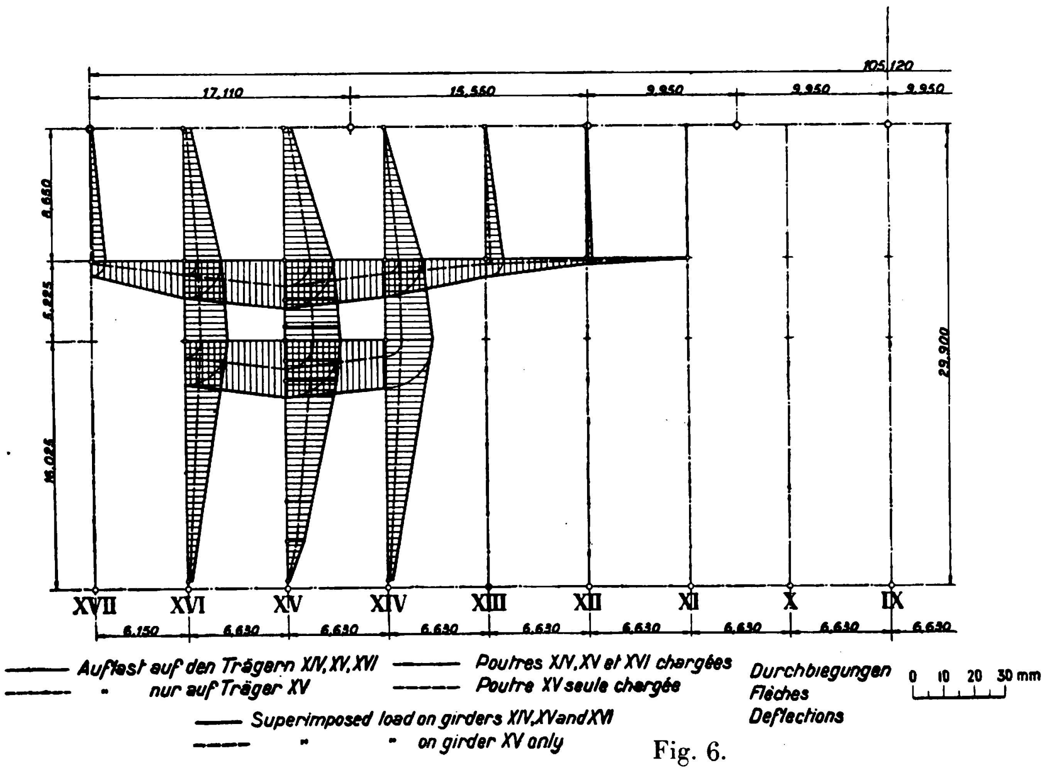


Fig. 6.

It may be observed that in the case of loading only one girder, the neighbouring girders contribute in notable proportions towards supporting the load. If three neighbouring girders are simultaneously loaded, it may on the other hand be observed from the diagram of deflections (thus considered as representing the influence lines) that the median girder supports about 75 % of the total load which would be applied to it, if alone.

6) *Results from the extensometers.*

The results thus obtained can be divided into three groups, according to the zone considered: first group, concerning the measures of deflections in section C (fig. 1), sufficiently distant from the singular points — second group, concerning the elbow zone A A — third group, concerning the elbow zone B B.

In each case the tests were repeated and the final results mentioned based on the average of at least 4 readings. The variations met with always remained very low and never exceed 10 %.

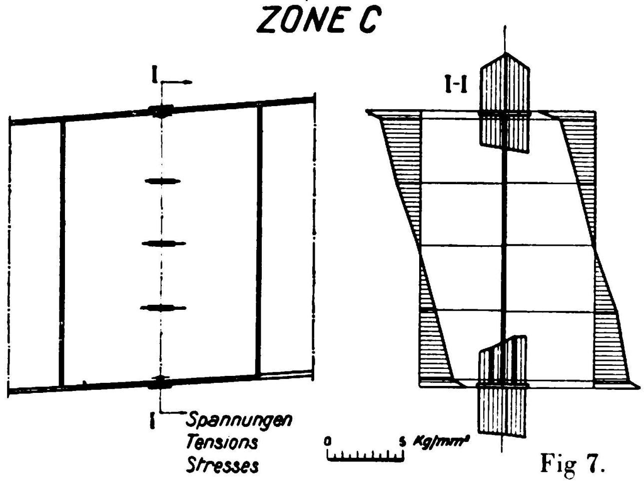


Fig 7.

The structure proved to behave as elastic, the residual deformations after application of the cycles of loadings always kept very low, even on the instruments situated at places corresponding to maxima of the stresses.

7) *Results concerning section C.*

The results of the tests of the first group are given in the diagram represented in table V (fig. 7). An examination of this diagram shows that the law of linear variation of stresses is pretty well in agreement with the results

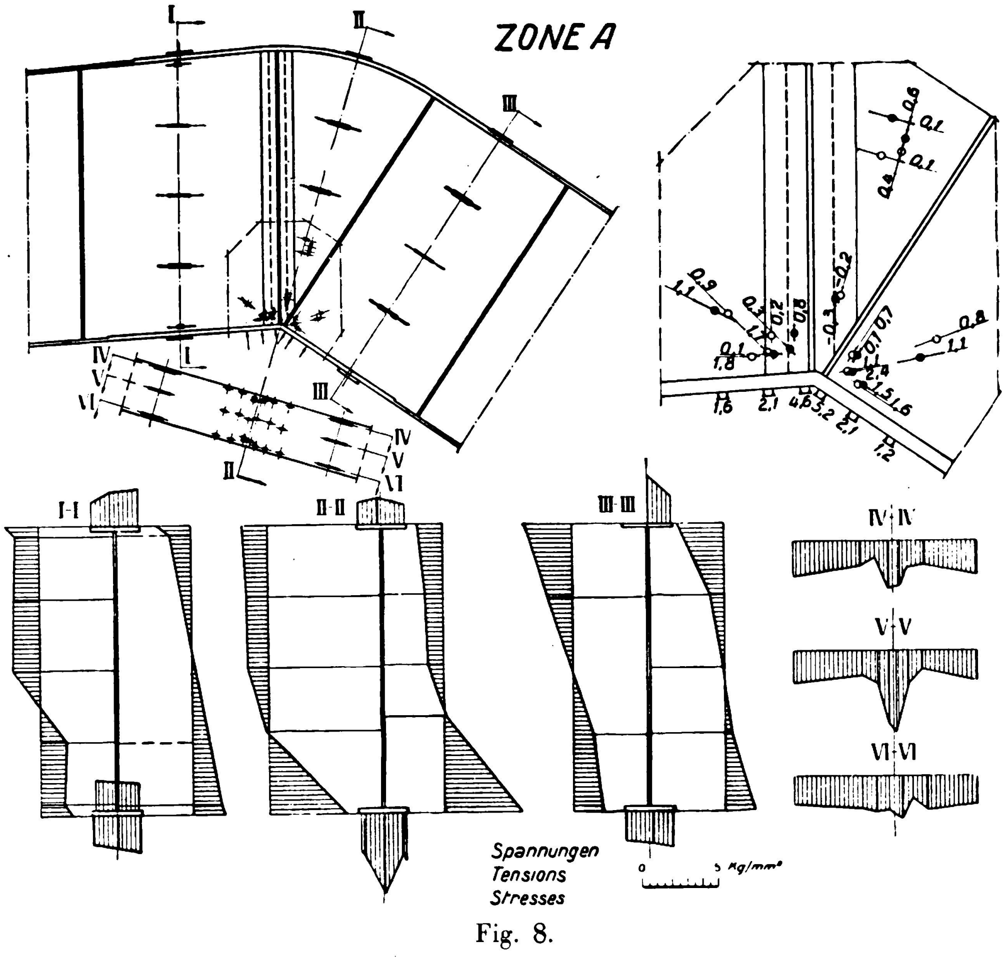


Fig. 8.

as regards the web, whereas deviations from this law can be observed for the flanges of the girder. This fact, which also appears in other cases, is all the more noticeable here, as, owing to the influence of the welding of the flanges on the web and on the ribs which stiffen the web itself, the flanges show a warping and a slight incurvation, both transversally and longitudinally (towards the interior of the girder). It follows that the internal face of the flange is not in a position to work exactly to the same amount as is the internal face.

From the diagram thus experimentally obtained, we can calculate the actual

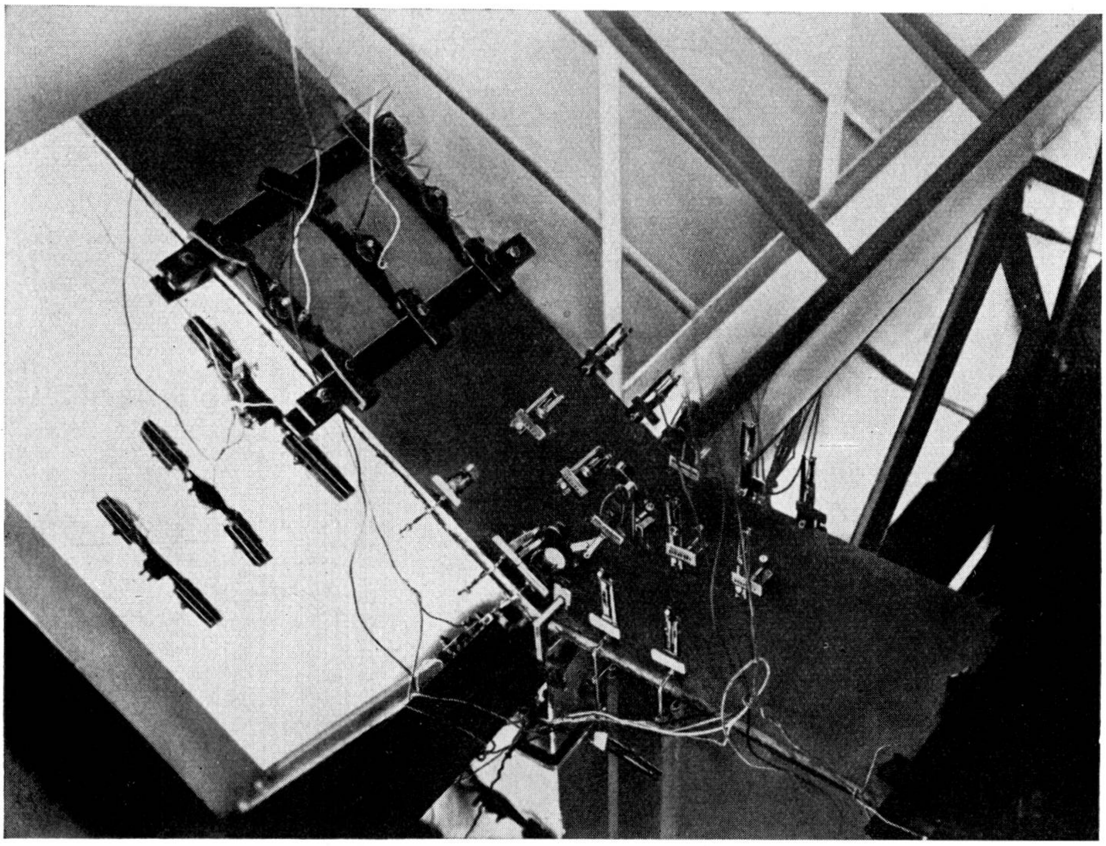

Fig. 9.

moments themselves with the necessary approximation by means of a graphical integration. The couple comes to an arm of about 1.40 meter and a force which is a little more than 50 tons.

Owing to the stresses which apply to the girder, the moment on the section considered ought to be about 90 tm. The actual value shows however a reduction of 30 % from this number and such a reduction seems to be due, for the greatest part, to the distribution of the load on the girders which are not directly loaded and on the auxiliary members; this view is in fair agreement with the results obtained from the preceding and direct measures of the stresses.

8) *Results about the elbow zone AA.*

The study of the elbow zone AA has been especially extended to the determination of the state of stresses in the neighbourhood of the lower elbow point.

The flange ought to form here a sharp angle; in fact, from the measurements taken at site, it results that the radius of curvature of the extreme fibre is 9.7 cm. Calculations and tests on models had shown an increase of stress which it was particularly interesting to corroborate. Diagram III (fig. 8) gives a sketch for the distribution of the extensometers in this zone. The instruments on the one face are indicated with full dots and those on the other are represented with plain circles. Fig. 9 gives an idea of the complexity of the arrangement and of the great number of instruments used.

Moreover diagram III, shows the average results of measurements taken from the three different sections through the elbow; section II passes through the centre of curvature of the elbow and sections I and III are placed symmetrically to section II.

The maximum stress measured is 5.2 kg/mm$^2$; it represents a variation of about 250 % from the average value at the end of sections II and III.

The experimental results thus obtained were compared with the results obtained from calculation. On the basis of the results concerning section II, as regards the stresses on the two faces of the web, a curve was drawn, representing the character of the stresses, the interpolation of which satisfies the values of the moments previously determined, during the above mentioned study of the normal zone C.

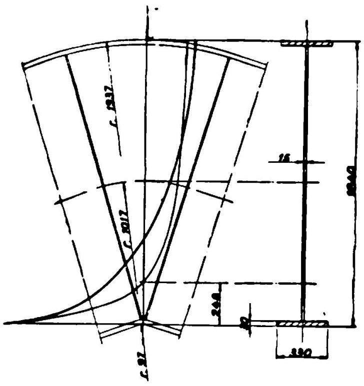

Fig. 10.

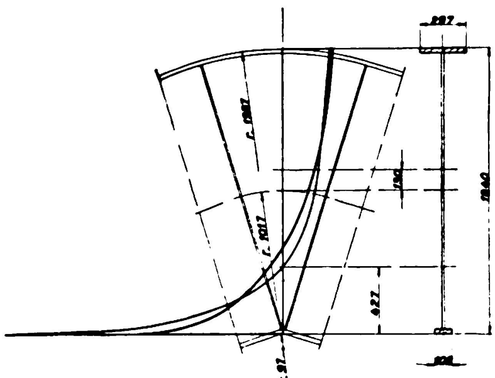

Fig. 11.

A comparison was made between this curve and the calculated curve. Three distinct studies were completed, using the known theory applying to girders with curvilinear axis.

a) *The section of the girder is considered as identical to the actual section.*

Under the assumption of equal moments, results were obtained which are given by diagram VI a (fig. 10). The fine curve represents the calculated curve and the thick line the experimental curve.

b) *The section of the girder is assumed to be reduced.*

The hypothesis recently put forward by *Bleich* (Stahlhochbauten, 2nd part. page 644) was applied in order to make allowance for the fact (since experimentally determined) that the stresses along the flange of the section are reduced towards the edges, owing to the influence of the transverse deflection of the flange itself. A supposed section was thus obtained and the corresponding results are illustrated in diagram VI b (fig. 11).

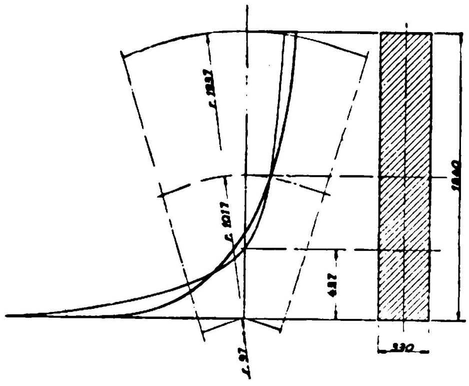

Fig. 12.

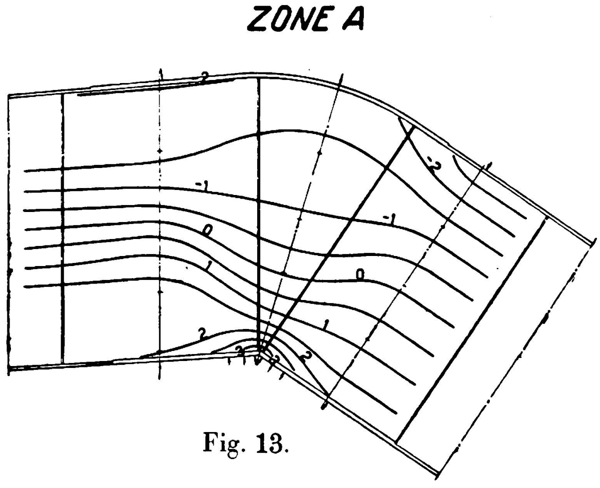


Fig. 13.

It is worth noting that the shapes of the theoretical and experimental curves are rather similar. The theoretical neutral point is located somewhat lower than in reality, but the deviation is however less noticeable than in the preceding case. The point which corresponds to the maximum of stress is notably different in the two cases. This was thought to be due to the two following facts: first, the instruments were applied on the web within a few centimeters of the respective section and therefore could not register the maximum of deformation; second, the bracing members effectively reduce the transverse deflection of the flange, resulting in greater uniformity for the stresses in the flange itself and

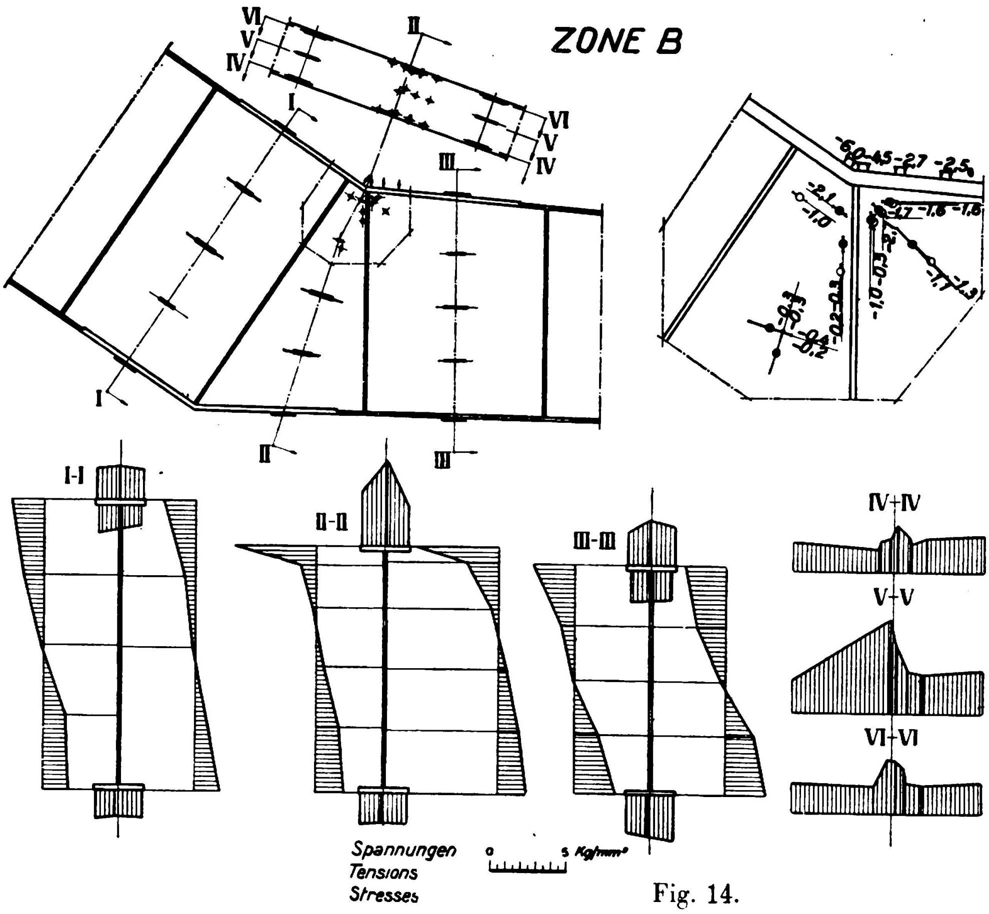


Fig. 14.

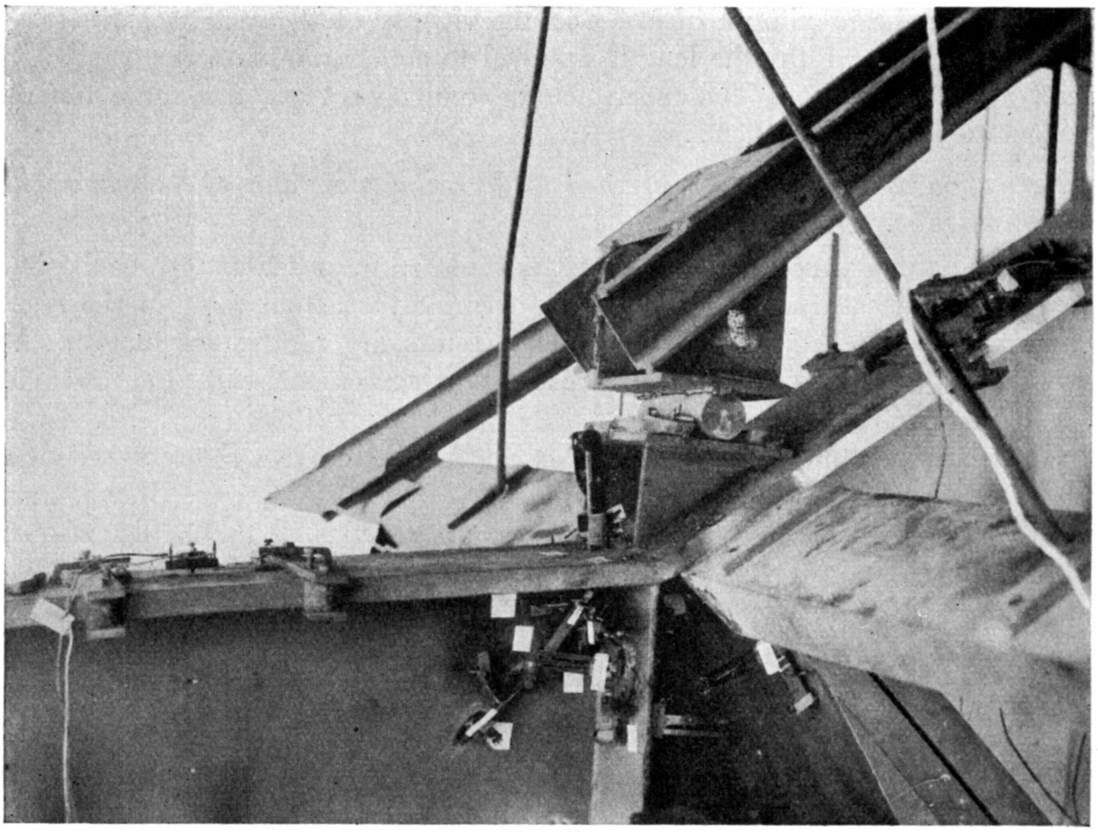

Fig. 15.

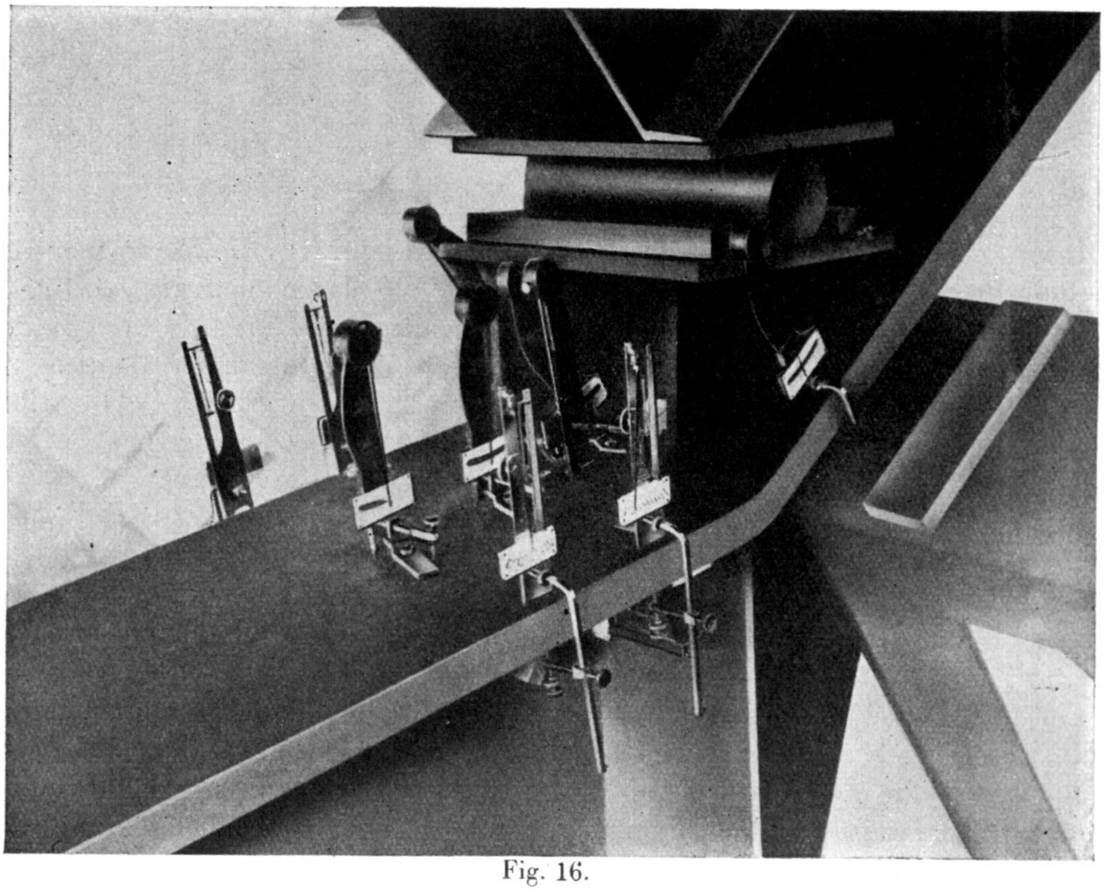

Fig. 16.

a reduction of the maximum of stress in the vicinity of the section, as in case a. In fact, the fictive width (the length assumed to collaborate with the web) of the flange, as deduced from the experimental results, is twice the value obtained by calculation (about 10,9 cm).

c) *The section of the girder is assumed to be rectangular and of the same width as the flange.*

The calculations were made, in the first place, in order to give a basis of comparison with cases a and b, and to dertermine the actual value of the results obtained from the photo-elastic tests. The results are plotted on diagram VIc (fig. 12); the photo-elastic values are in fair agreement with the calculated values (fine curve).

In order to complete the study of zone A, the curve of stresses deduced from the experimental values and accounting for expansion were drawn, longitudinally as well as transversally with respect to the axis of the girder; diagram VIII was thus obtained (fig. 13), in which the numbers indicate the stresses in kg/mm².

ZONE B

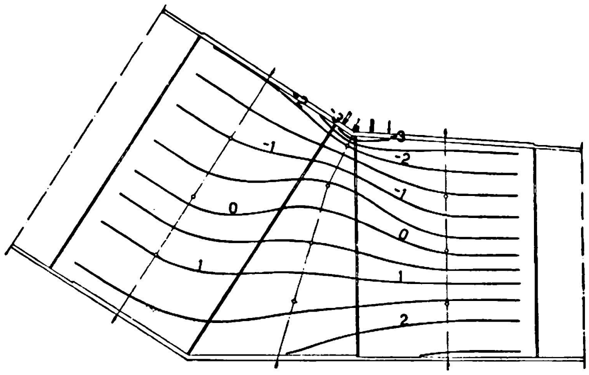


Fig. 17.

It is worth noting that the shape of these curves is greatly similar to the shape of the curves which were obtained from the photo-elastic method (see fig. 3). It will be noticed that the inflection of the neutral axis towards the elbow is characteristic, as well as the reduction of stresses near the upper flange.

Under conditions similar to those created for the elbow zone AA, the elbow zone BB was studied experimentally (see fig. 1). The arrangement of the extensometers and results obtained are plotted on diagram IV (fig. 14).

Photographs 15 and 16 represent the arrangement of some instruments applied in this zone, for two different phases of the measurements, the first phase with intervention of the load concentrated near the elbow and the second phase, on the other hand, with elimination of the action of this load during the test.

For this elbow, the maximum of measured stress of 6 kg/mm² was obtained, with a localized deviation of about 240 %, in spite of notable stiffening influences in the most loaded part, these influences contributing in effectively reducing the stresses at the elbow, as was ascertained from the indications of the instruments.

Diagram VII (fig. 17) reproduces the curves of normal stresses for this zone. These stresses display notably similar to the curves which were determined photo-elastically for the case of the plane.

## Summary.

The supporting members of the roof of the new station at Florence consist of girders the axis of which affords two opposite and sharp bends. These I-Section girders, electrically welded, cover a span of about 30 m and their maximum depth is 1,84 m. In order to dertermine the shape of the curves of stresses for the two elbows, a series of tests has been made.

Measurements were first carried out on a reduced and transparent model, by photo-elastic methods, then on a steel model which reproduced the actual girders at the scale of 1/5. The results thus obtained were then controlled by measurments taken on the girders themselves, after erection of the structure.

The authors describe, in the present report, all the tests which have been carried out, the instruments which were employed and their arrangement. They comment the resuts obtained. A series of diagrams gives the curves of measured stresses. Other figures allow for a comparison, for the elbows, between calculated and measured stresses.

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