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Splitting and Tear Tensile Stresses in Rectangular Plates Loaded at Varying Distances from the Plate Corner

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PREFACE

The Division of Building Research has been interested in precast concrete construction in general for a number of years and more recently has been involved in an active research programme on the connections between precast structural members. One of the more fundamental problems in this area is the bearing capacity of concrete under a line load parallel and near to edge, as for instance in the head of a column carrying one or more beams or in a bracket.

The results of the Swedish studies presented in this paper, contribute greatly to an understanding of the stress distribution and of the mechanism involved in the failure of concrete subjected to such loads. This translation is therefore provided to make this information more readily available to designers and others involved in the field of precast concrete.

The translation has been prepared by W.R. Schriever, Head, Building Structures Section, Division of Building Research, National Research Council.

Ottawa
July 1964

R.F. Legget
Director

NATIONAL RESEARCH COUNCIL OF CANADA

Technical Translation 1137

Title:	Splitting and tear tensile stresses in rectangular plates loaded at varying distances from the plate corner (Spalt- und Abreisszugspannungen in rechteckigen Scheiben, die durch eine Last in verschiedenem Abstand von einer Scheibenecke belastet sind)
Authors:	R. Hiltscher and G. Florin
Reference:	Bautechnik, 40 (12): 401-408, 1963
Translator:	W.R. Schriever, Division of Building Research, National Research Council

SPLITTING AND TEAR TENSILE STRESSES IN RECTANGULAR PLATES LOADED AT VARYING DISTANCES FROM THE PLATE CORNER

Summary

In rectangular plates which are loaded at various distances from one corner by a short strip load, two types of tensile stresses occur: splitting tensile stresses below the load and tear tensile stresses (which tend to tear off the corner) beside the load. These two types of tensile stresses are investigated systematically in the present paper, as a function of the geometrical dimensions and the load position, by means of model tests. From this the corresponding tensile stress diagrams are derived for the design of the reinforcing.

1. Introduction

In an earlier paper(1) the author dealt with the splitting tensile stresses and the resulting splitting tensile force produced in a plate loaded in the centre by a strip load of varying size. Besides these splitting tensile stresses, which are formed in a certain zone below the load, there is also another type of tensile stress which occurs on both sides of the load. These two types of tensile stresses have already been calculated by, among others, Guyon(2), by means of an approximate solution for an infinitely high strip loaded along its small side. Sargious(3) determined these stresses as well as the resulting "edge tensile forces" along the side of the stress block of a prestressed beam in an experimental way, and Javornicky(4) studied these tensile stresses and the tensile force for a plate loaded by several loads. The purpose of the present paper is a systematic study of both types of tensile stresses in loaded plates for a variation of dimensions and load positions within wide limits, in which special attention has been given to the problem of a loaded plate corner.

2. Testing Technique

For the investigation, which is to replace as much as possible the exact solution of the problem by the theory of elasticity, the author has used the optical stress analysis standard method, which today is considered as the most accurate and most suitable model method for the experimental study of dimensional stress problems. The difference of the two principal stresses, as well as the direction of the major principal stresses, were determined with a polariscope, and the sum of the principal stresses with a lateral extensometer according to Hiltscher(5-7). For the evaluation of the measurements (that is the calculation of the stresses σ_1, σ_2, σ_x, σ_y and τ_{xy} at every measuring point), an electronic calculator has been used, although the calculation in itself is very simple. Figure 1 shows the isochromatic lines of a plate loaded near the corner. The model, the fixity along the lower edge, the details of the production of a uniformly distributed load, and the model laws have been described in Reference 1. The load was produced by a lever arm and weight through an extremely well controlled vertical spindle so that in the loaded condition the load was vertical within ±30 seconds arc. The room temperature was maintained with $\pm\frac{1}{2}$°C in order to avoid changes of the elastic and optical constants.

3. Preliminary Tests to Obtain Over-all Impression

Prior to the planning of the many tests it was necessary to obtain an over-all impression of the problem. This was done by means of preliminary tests on square plates, fixed at the bottom as shown in Reference 1, with the dimensions 200 × 200 × 10 mm which were loaded in the middle, near a corner, and in an intermediate position by a narrow, uniformly distributed strip load. The horizontal stresses σ_x obtained in the three cases are shown in Fig. 2 - 4. For the case of central load (Fig. 2), which thus corresponds exactly to the cases studied in Reference 1, the zone of splitting tensile stresses σ_x starts rather deep under the load and extends laterally and downwards in the shape of a leaf. The maximum splitting tensile stresses and the maximum splitting tensile force appear in the plane of symmetry. Separated from the zone of splitting tensile stresses, on both sides of the load, there are other additional tensile zones whose maximum tensile stresses are near the edge. In the case of the central loading the maximum of these edge tensile stresses, which can be linked to the settlement of the plate edge under the influence of the load, is somewhat smaller than the maximum splitting tensile stresses. The resulting tensile force is, however, very small.

Note: It should be explained here why only the horizontal tensile stresses σ_x are given. In principle a presentation by means of the major principal stresses and the stress trajectories, as they are used in photoelasticity(4), would be more complete and more accurate. The civil engineer, however, is not accustomed to thinking of principal stresses; he prefers the presentation in the form of the stress components σ_x, σ_y and τ_{xy}. He would furthermore hardly follow the tensile stress trajectories slavishly for the reinforcement, instead he divides it usually into tensile reinforcement parallel to the edges of the member, and additional shear reinforcement. In the present case moreover, the maximum splitting tensile stresses directly under the load, and the largest "edge deformation tensile stresses" (later called tear tensile stresses) in and near the upper plate edge are almost identical by either method. Only in the areas of relatively small tensile stresses do we find the trajectories of the principal stresses differing significantly from the x direction and the major principal stress σ_1 a little greater than σ_x. Thus the presentation of the stress σ_x alone seems to be justified. A special advantage rests in the fact that in this way a division into zones of the splitting and tear stress is attained (see Fig. 2 - 4 and 6 - 22), which helps considerably in the understanding of the over-all stress pattern. This presentation furthermore offers an opportunity to superimpose tensile stress patterns for several loads in a simple way since stress σ_x can be directly added.

If the load is shifted more towards the corner of the plate the zone of the splitting tensile stresses shrinks more towards the load, and the maximum splitting tensile stress decreases. At the same time the tensile stress along the upper plate edge and the resulting maximum tensile force from these tensile stresses along the "inside" of the load increases several fold.

This edge increase in the tensile stresses and the tensile force sideways from the load is due no longer, as in the previous case, solely to the local settlement of the plate edge under the influence of the load, but now mainly to the unsymmetrical spreading of the "pressure force flow" on to the load. Whereas this flow can still spread into the plate on the side towards the middle, the corresponding area of plate on the side towards the corner is missing, and the support from the outside is smaller. In order to establish equilibrium, appropriate tensile stresses and tensile forces have to occur in the plate, especially on the side towards the middle from the load. Since these stresses and forces, which include the local edge deformation tensile stresses and tensile forces mentioned before, produce tearing forces on the loaded corner, the terms <u>tear tensile stresses</u> and <u>tear tensile forces</u> are introduced.

If now the load is shifted completely to the corner of the plate, the area of splitting tensile stress is reduced to a very small zone directly under the load and furthermore merges with the area of tear tensile stresses. The splitting tensile stresses are somewhat reduced, the splitting effect is smaller and the spreading of the pressure force flow or the pressure force lines(1) is possible towards one side only. Due to the simultaneous considerable reduction of the splitting tensile zone, the maximum splitting tensile force decreases to a very small value. The tear tensile stresses and tear tensile forces on the other hand reach a maximum value for the case of the load at the corner and are therefore completely predominant.

4. Test Planning

On the basis of the pilot tests the necessary number of models and tests for the experimental study of the over-all problem can now be determined. The following symbols have been introduced (Fig. 5):

h = height of plate
b = width of plate
a = width of load
d = distance from the corner
t = thickness of plate
σ_{x_S} = maximum splitting tensile stress
σ_{x_A} = maximum tear tensile stress
q = P/at reference stress
H_S = maximum splitting tensile force
H_A = maximum tear tensile force
y_{H_S} = distance of the resulting maximum splitting tensile force from the upper plate edge
y_{H_A} = distance of the resulting maximum tear tensile force from the upper plate edge
y_{H_A} = distance of the cross-section with the maximum tear tensile force from the vertical edge of the plate nearest to the load.

With these symbols one obtains the following parameters for the presentation of the splitting and tear tensile stresses and the splitting and tear tensile forces.

(a) The load concentration factor b/a

The minimum value is $b/a = 1$ for the case of the uniformly distributed load for which no splitting or tear tensile stresses occur. For a value $b/a = 30$, according to Reference 1, the splitting tensile force is practically independent of the load concentration factor and for the tear tensile force the same should be true in an approximate way. Therefore this value was used as the upper limit instead of $b/a = \infty$. Between $b/a = 1$ and $b/a = 30$ one other model with $b/a = 10$ was introduced.

(b) The relative plate height h/b

The lower limiting value of the relative plate height is $h/b = 0$. As an upper limit $h/b = 2$ was selected for the experiments since according to Reference 1 the splitting tensile force increases only slightly between $h/b = 2$ and $h/b = \infty$. (The tear tensile force would probably depend even less on the relative plate height since the tear tensile force is greatest near the top of the plate.) Between these limiting values models with relative plate heights $h/b = 0.5$ and $h/b = 1.0$ were obtained by reduction of the higher models.

(c) The relative load distance from the corner $2d/a$

Starting from the load position at the corner with $2d/a = 1$, two further load positions were studied for the models with $b/a = 10$, and for the models with $b/a = 30$ three further load positions. The load position at the plate centre, $2d/a = 10$ for $b/a = 10$ and $2d/a = 30$ for $b/a = 30$ had already been investigated(1) and was only supplemented in appropriate parts.

In order to give the model plate a well defined support, it was cast(1) along its lower edge into a sufficiently large block of the same material (Araldit) which then could be placed on a base in any desired way. This type of model support corresponds also in its first approximation to the practical case of the fixing of a wall plate in rock, a case which is very common in Sweden. If, however, the plate is fixed in a rather small foundation which in turn is elastically supported on soft ground, deviations in the tear and splitting tensile force can occur, especially for smaller plate heights, which should be studied further.

5. Measurements and Evaluation

For the 17 load cases mentioned (using 5 different models), the sum of the stress, the difference of the major principal stresses, and the direction α of the major principal stress σ_1 was determined for all measuring points on a number of cross-sections which were selected on the basis of the results of the pilot tests. After evaluation by means of electronic computer, stresses σ_x, with which we are here concerned, were plotted in dimensionless form with the mean loading intensity $q = P/a \cdot t$ as a reference stress. The stress distributions for the various cases are shown in Fig. 6 - 22 and the resulting maximum stresses are given in Fig. 23 and 24. From all the stress distributions the resulting splitting or tearing tensile forces were derived by graphical integration, and their distance from the loaded edge y_{H_S}/a or y_{H_A}/a, as well as the distance x_{H_A}/a of the cross-section with the maximum tear tensile force from the vertical edge nearest the load were determined. These values, together with the maximum tensile stresses of Fig. 23 and 24, generally describe the splitting and tear tensile effect for each case. They are shown in Fig. 25 and 26 for the investigated load concentrations $b/a = 10$ and $b/a = 30$ as functions of the distance of the load from the corner, $2d/a$, and of the relative plate height. In the perspective diagrams of Fig. 27 and 28 the split and tear tensile forces are given as functions of the three parameters b/a, h/b and 2d/a.

6. Accuracy of the Stress Determination

In the determination of the stresses σ_x and σ_y according to the well known formulae

$$\sigma_y = K\Delta t + Sn \cos 2\alpha,$$

$$\sigma_x = K\Delta t - Sn \cos 2\alpha.$$

where Δt = change of thickness at the model point,
n = isochrome order at model point,
α = the angle of the larger principal stress σ_1 with the vertical in the model,
K = "lateral constant"(7) for the model ($k/cm^2 \cdot$ graduation),
S = isochrome value (photoelastic constant) for the model ($k/cm^2 \cdot$ order),

we have the measuring errors which occur in the determination of the three measured values Δt, n and α and the errors produced by the temperature dependence of the calibration values K and S, and also any errors produced by undetermined temperature variations. In order to obtain an idea of the accuracy of the stress determination, the stress values determined at different times on a special model of a diametrically loaded circular plate whose stress condition can be calculated rigorously, were compared with the calculated values which in principle are free from errors. The root mean square m of the absolute error in the determination of σ_x and σ_y (not to be confused with the standard deviation of the mean value) was determined and yielded the following which is almost independent of the stress value

$$m = \sqrt{\Sigma e^2/n} = 0.18 \text{ kg/cm}^2,$$

where $e = \sigma - \sigma_{meas}$,
n = number of the measurements.

This mean value of the absolute error represents an accuracy of the stress determination of approximately ±0.5% for the maximum tear tensile stresses of approximately 0.4q in the present investigation, equivalent in the test to approximately $\sigma_x = 34$ kg/cm^2. This represents for the maximum splitting tensile stresses (Fig. 23 and 24), which are only about 1/5th of the former, an accuracy of ±2.5%.

7. Discussion of Results

The maximum tear and splitting tensile stresses are shown in Fig. 23 and 24 as functions of the various parameters. As was stated in Section 3, the tear tensile stresses are considerably larger than the splitting tensile stresses, especially for load positions near the corners of the plate. Only for the symmetrical position of the load are the splitting tensile forces somewhat greater than the tear tensile forces. Both types of stresses are relatively independent of the relative plate height h/b when this ratio is not too small. The splitting tensile stresses depend on the spreading of the force lines, varying with the load position, in the plate under the load. They are at a maximum for a load position of 2d/a of approximately 2 - 4. With increasing load concentration factors the tear tensile forces increase for the various load positions, whereas the splitting tensile forces tend to show an opposite trend. The maximum of the splitting tensile stresses occurs always in the load cross-section, although at varying depth. The maximum of the tear tensile stresses occurs in the upper face of the plate, in all cases at about 1 - 1.5a sideways from the load. The fact that the maximum value of the tensile stress does not occur immediately at the side of the load, as is sometimes indicated in literature, is due to the following reason; the edge stresses which result from the concave depression under the load are compressive stresses in the immediate vicinity of the load and therefore compensate the tear tensile stresses at this point.

Considering now the tensile forces (Fig. 25 and 26) corresponding to these split and tear tensile stresses, we find for the tear tensile force a similar picture to the case of the maximum tear tensile stress: a steep increase for a load approaching the corner, a relatively small dependence on the relative plate height and an increase with an increasing load concentration factor. The splitting tensile force, which depends not only on the maximum splitting tensile stress but also on the varying depth distribution of the splitting tensile zone, is (with the exception of the load positions near the corner of the plate where it is quite small in any case), dependent on the relative plate height h/b. This force increases for the greater plate heights (h/b greater than 2) with increasing load distance from the corner first rapidly and then more slowly, while the effect of the fixity along the lower plate edge in decreasing the splitting effect is felt more and more as the relative plate height decreases. This fixity effect reaches a maximum for the symmetrical position of the load and increases furthermore with the load concentration factor.

The position of the cross-section with the maximum tear tensile force with regard to the nearest vertical plate edge, x_{H_A}/a, increases with the load distance from the edge and is relatively independent of the relative plate height, but increases rather considerably with the load concentration factor. From the diagrams of Fig. 6 to 22 it can be seen that the maximum of the tear tensile force is always rather flat and not very pronounced. This was also indicated in Reference 8.

Whereas the location of the resulting tear tensile force with regard to the located edge y_{H_A}/a, depends relatively little on the various parameters, the resultant of the splitting tensile force is located the lower below the plate edge the greater the load distance from the edge, the relative plate height, and the load concentration factors become.

In case several loads are applied at the same time, the stress diagrams of Fig. 6 to 22 can be superimposed appropriately and in this way the maximum tensile stresses and forces can be determined, at least approximately.

8. Consideration of the Design of the Reinforcing

By means of the diagrams of Fig. 23 and 24 the maximum tear and splitting tensile stresses can first be determined. From this it can be decided whether, with regard to the tensile strength of the concrete used and with regard to any other requirements, any reinforcing is necessary.

If the reinforcing is required for one or both types of tensile stresses, then the appropriate total amount of reinforcing can be determined from Fig. 25 to 28 for the maximum tear and splitting tensile force. If the reinforcing is not divided any further, then also the exact height of the corresponding resulting force y_{H_A} or y_{H_S} can be read from Fig. 25 and 26. In general, however, it is recommended to distribute the total reinforcing requirements according to the distribution of tensile stresses within the section. This can be done to any desired degree of refinement by means of the stress distribution given in Fig. 6 to 22. It is especially desirable to distribute the steel section appropriately for the case of splitting tensile force for a load in the centre, because in this case the tensile zone has a considerable depth. From the diagrams of y_{H_A} and y_{H_S} (Fig. 25 and 26) it can be seen that for load positions directly on, or close to the corner, the resultant of the two tensile stress types nearly coincide. It is therefore sufficient in this case to use the same reinforcement for both types of tensile stress, whereas, for the load in the middle, the centre of the reinforcing for the splitting tensile force is considerably lower than for the tear tensile force.

The necessary length of the reinforcing bars can be assumed from the tensile stress distribution given in Fig. 2 to 4 and 6 to 22.

9. Additional Test

It should be stressed once more that for the present investigation fixity of the plate on the base or on a very large foundation block of the same modulus of elasticity has been assumed. This type of foundation is easily defined and easy to reproduce in the test, which contributes considerably to the accuracy of the study.

In practical cases, however, the plate is usually supported on a yielding foundation, a fact which can result in changes in the splitting and tear tensile stresses, especially for relatively small plate height. In order to obtain an idea of the deviation from the present conditions the example shown in Fig. 29 was studied as an extreme case.* The model plate had a relative height $h/b = 0.5$ and was founded through a strip footing on a base of a material with a modulus of elasticity which was 60% of that of the plate. Measurements were made of the splitting and tear tensile stresses for the case of the load at the corner as well as at the centre.

For the centre location of the load the following was obtained: the splitting tensile stresses are in this case superimposed on bending stresses, as the plate behaves somewhat like a beam on an elastic foundation. Since the flexural stresses in the upper part of the plate are compressive stresses, they compensate to a large extent not only the splitting tensile stresses, but also the tear tensile stresses (which in this case would better be called the edge deformation stresses), whereas near the lower edge of the plate tensile stresses occur which are of the same order of magnitude as the tear tensile stresses in the "normal case". These can be calculated according to the theory of a beam on an elastic foundation.

For the position of the load near the corner of the plate the tear tensile stresses are approximately ten times as great, and the splitting tensile stresses approximately two and one-half times as great as for the central load position, so that the influence of moderate beam flexural stress is relatively small.

With the corrections made on the basis of this additional test, the results of the present investigation can now be used with good approximation, also for cases in which the support of the plate deviates from the original assumption.

Finally the authors would like to thank Mr. L. Strindell for the conscientious execution of the measurements.

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* This test was suggested to the author by Prof. Hubert Rusch.

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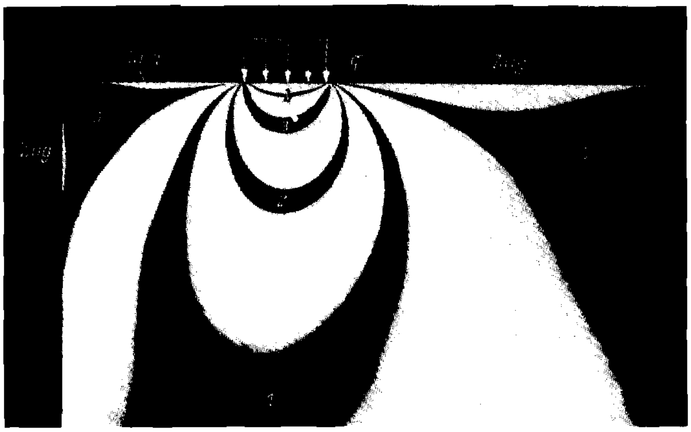


Fig. 1

Isochromatic picture of the plate loaded near one corner by a small uniformly distributed strip load

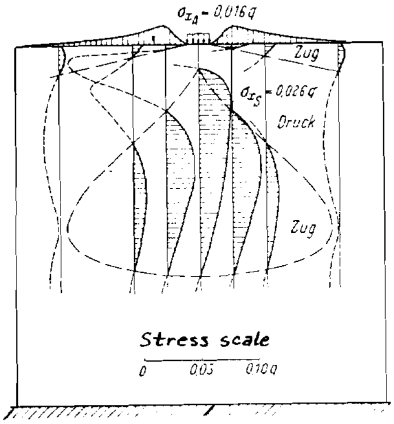


Fig. 2

Tensile zones with horizontal tensile stresses σ_x in a plate loaded in the middle
$h/b = 1$, $b/a = 16.66$, $2d/a = 16.66$

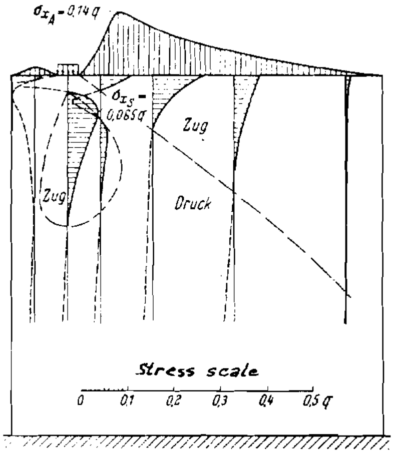


Fig. 3

Tensile zones with horizontal tensile stresses σ_x in a plate loaded near the edge
$h/b = 1$, $b/a = 16.66$, $2d/a = 5$

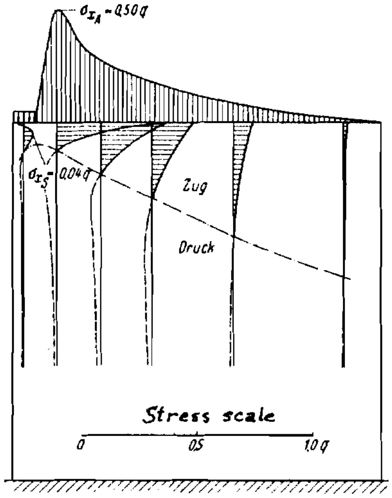


Fig. 4

Tensile zones with horizontal tensile stresses σ_x in a plate loaded at the corner
$h/b = 1$, $b/a = 16.66$, $2d/a = 1$

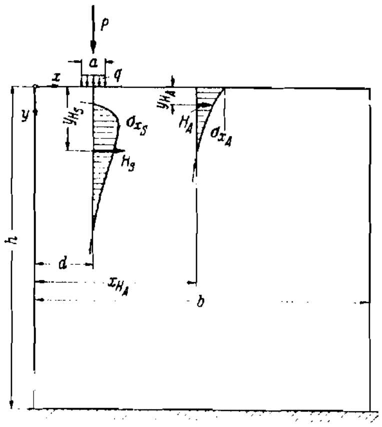


Fig. 5

Nomenclature

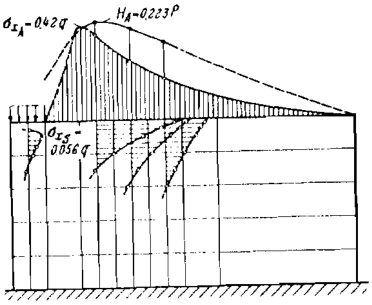


Bild 6. $h/b = 0{,}5$ $2\,d/a = 1$

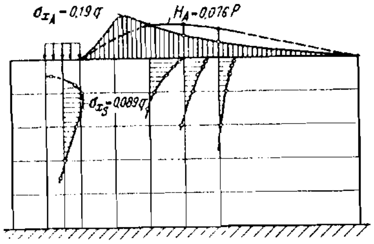


Bild 7. $h/b = 0{,}5$ $2\,d/a = 3$

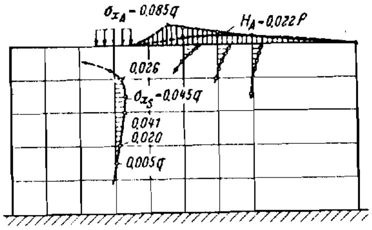


Bild 8. $h/b = 0{,}5$ $2\,d/a = 6$

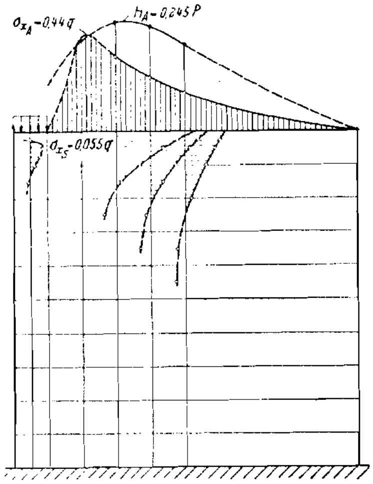


Bild 9. $h/b = 1$ $2\,d/a = 1$

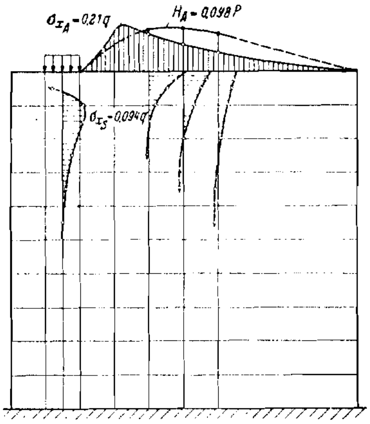
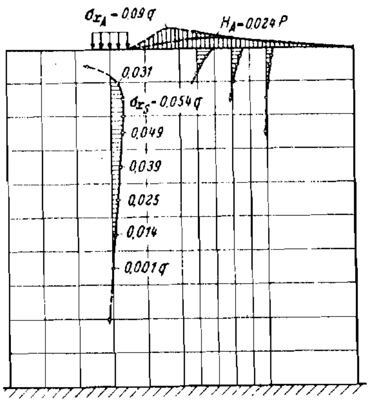


Bild 10. $h/b = 1$ $2\,d/a = 3$



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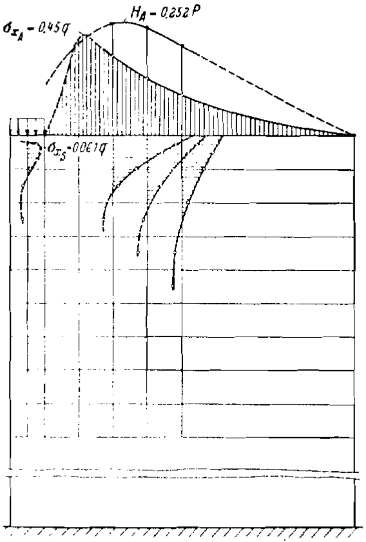

Bild 12. $h/b = 2$ $2\,d/a = 1$

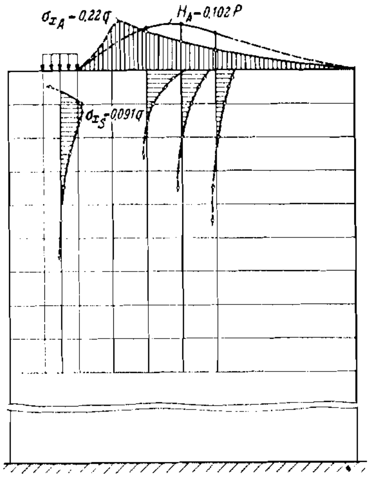

Bild 13. $h/b = 2$ $2\,d/a = 3$

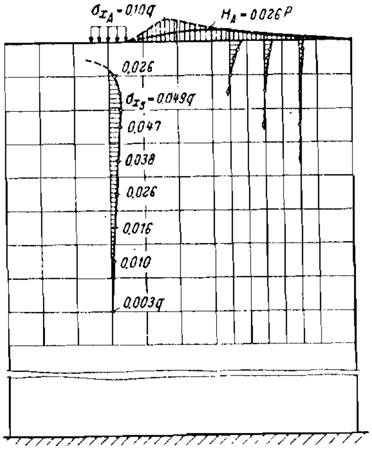

Bild 14. $h/b = 2$ $2\,d/a = 6$

Fig. 6 to 14

Splitting and tear tensile stresses σ_x in a plate loaded by a strip load with a load concentration factor b/a = 10 at various distances 2d/a from the corner, for various relative heights h/b

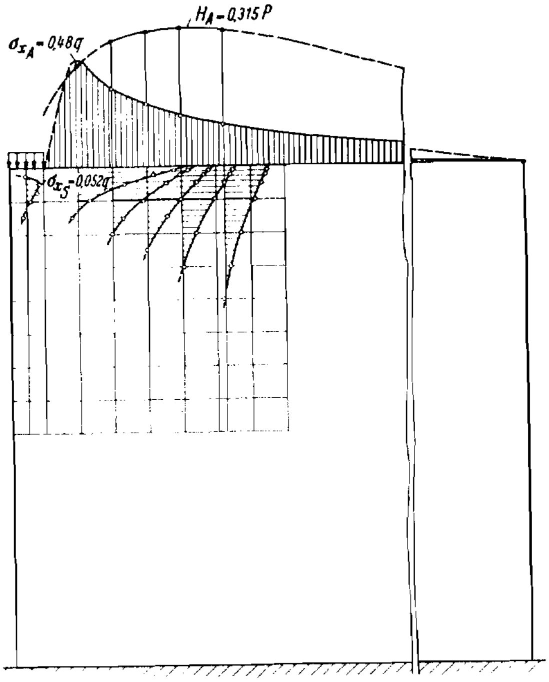

Bild 15. $h/b = 0{,}5$ $2\,d/a = 1$

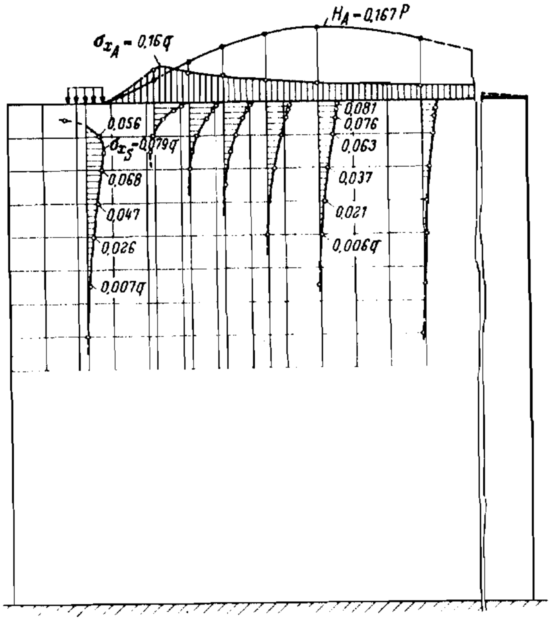

Bild 16. $h/b = 0{,}5$ $2\,d/a = 4{,}5$

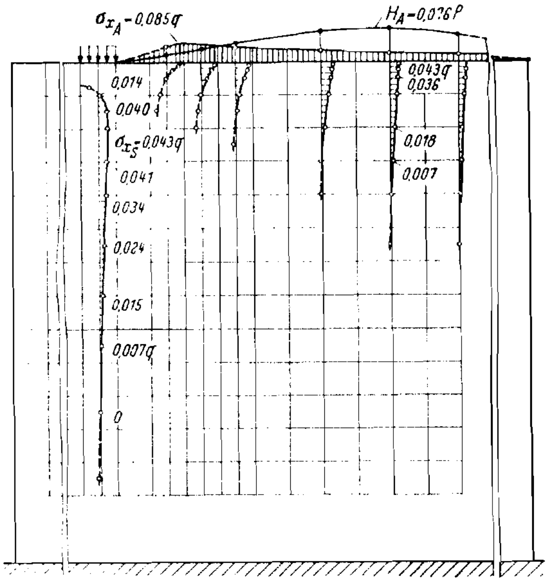

Bild 17. $h/b = 0{,}5$ $2\,d/a = 9$

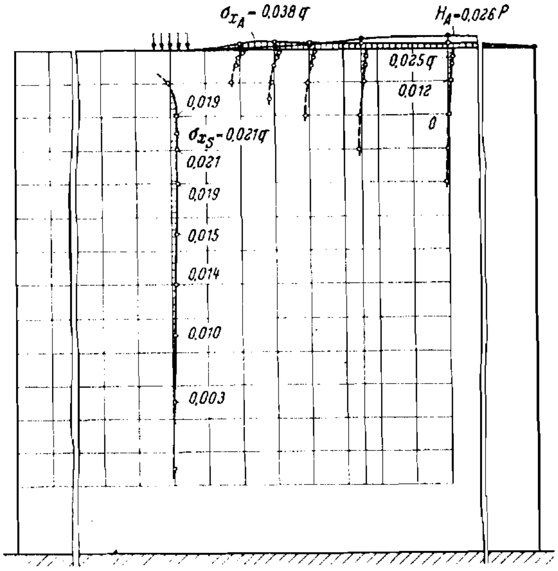

Bild 18. $h/b = 0{,}5$ $2\,d/a = 18$

Fig. 15 to 18

Splitting and tear tensile stresses σ_x in a plate loaded by a strip load with a load concentration factor $b/a = 30$ at various distances $2d/a$ from the corner, for various relative heights h/b

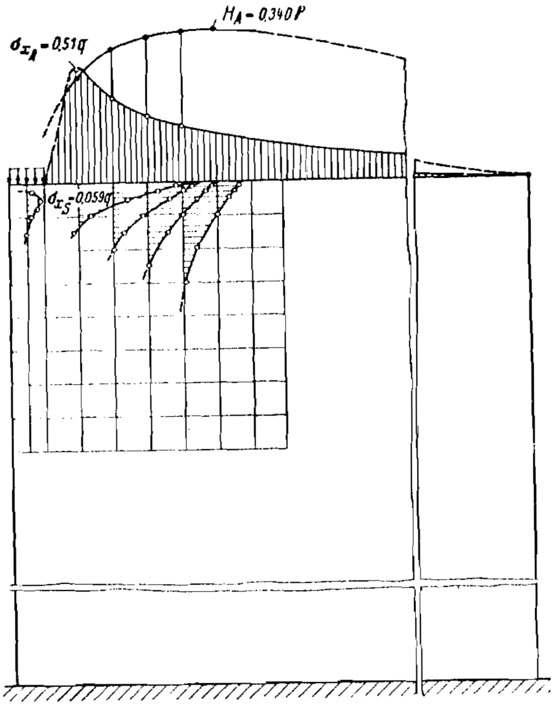

Bild 19. $h/b = 1$ $2\,d/a = 1$

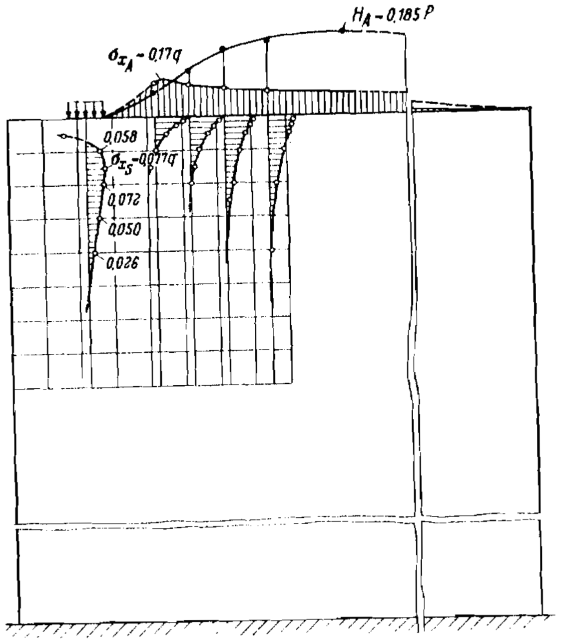

Bild 20. $h/b = 1$ $2\,d/a = 4{,}5$

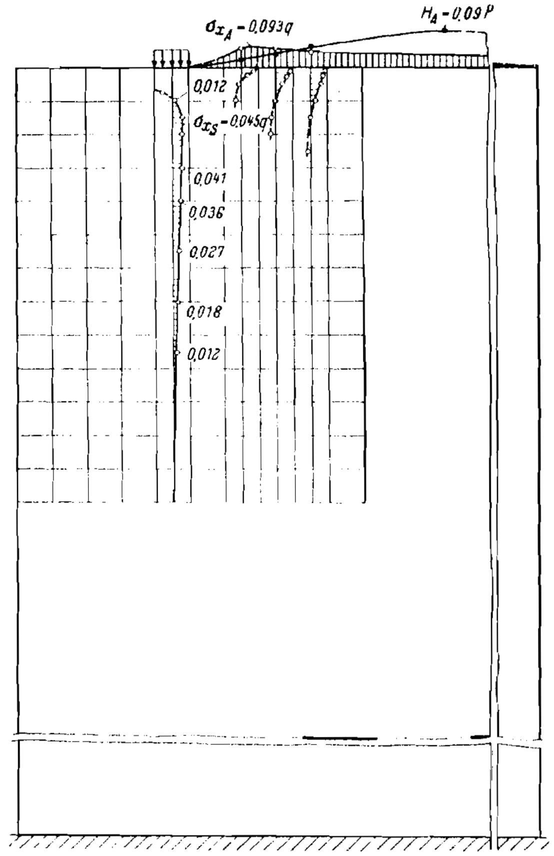

Bild 21. $h/b = 1$ $2\,d/a = 9$

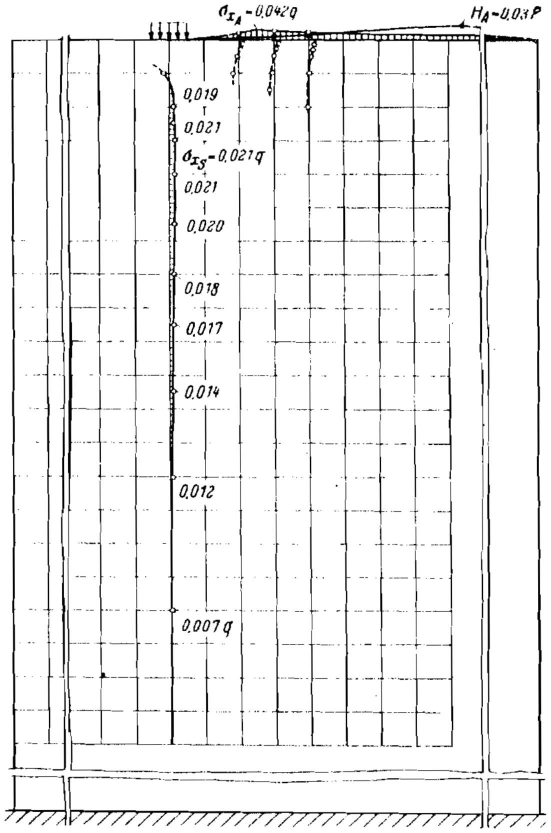

Bild 22. $h/b = 1$ $2\,d/a = 18$

Fig. 19 to 22

Splitting and tear tensile stresses σ_x in a plate loaded by a strip load with a load concentration factor $b/a = 30$ at various distances $2d/a$ from the corner, for various relative heights h/b

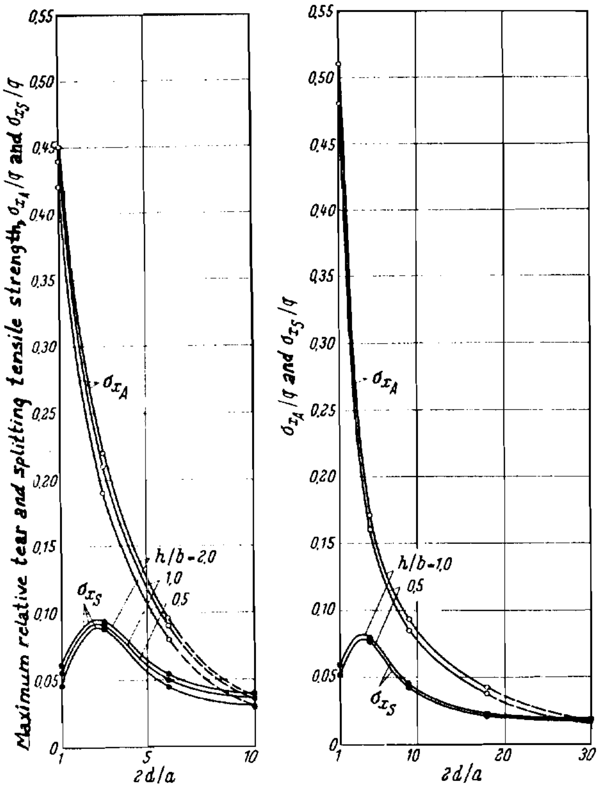

Bild 23.
Load concentration factor
b/a = 16

Bild 24.
Load concentration factor
b/a = 30

Fig. 23 and 24

Maximum tear and splitting tensile stress σ_{x_A} and σ_{x_S} as functions of the load distance 2d/a from the corner

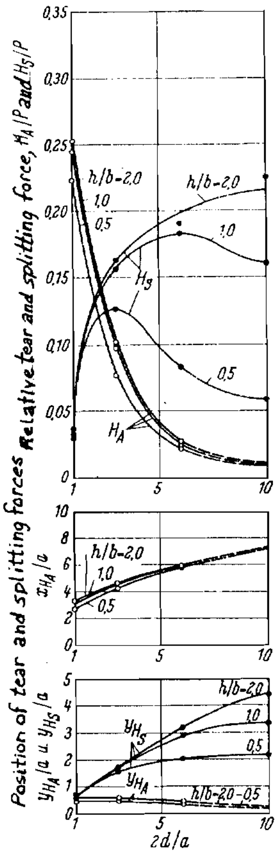

Bild 25.
Load concentration factor
b/a = 10

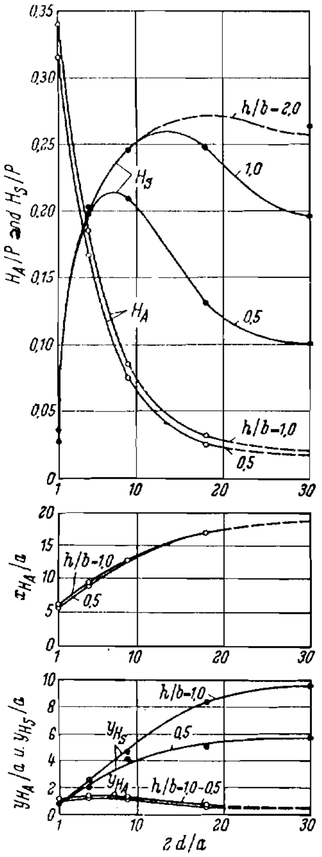

Bild 26.
Load concentration factor
h/a = 30

Fig. 25 and 26

Tear tensile force H_A/P and splitting tensile force H_S/P and their position with regard to the loaded edge (y_{H_A} or y_{H_S}), together with the distance of the cross-section with the maximum tear tensile force from the vertical edge nearest to the load (x_{H_A}), as a function of the distance of the load from the corner (2d/a) and of the relative plate height h/b

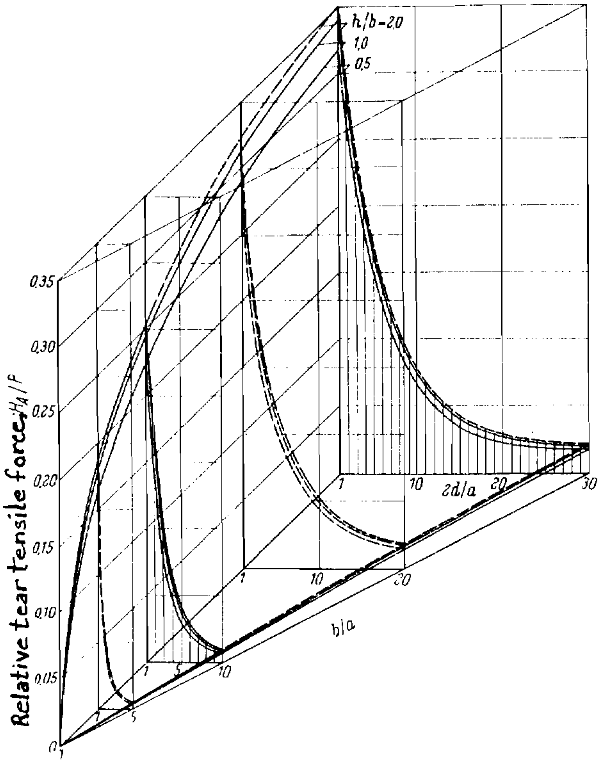

Fig. 27

Tear tensile force H_A/P as a function of the distance of the load from the corner 2d/a, of the load concentration b/a, and of the relative plate height h/b

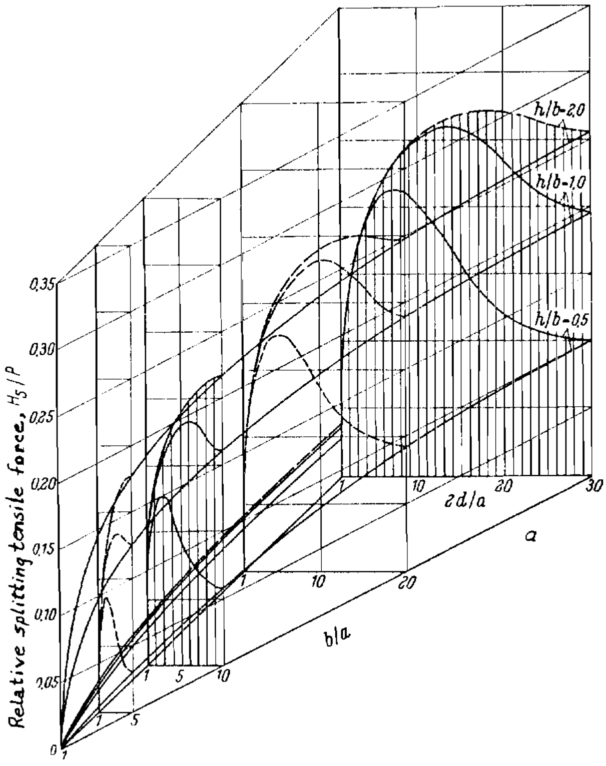

Fig. 28

Splitting tensile force H_S/P as a function of the distance of the load from the corner 2d/a, the load concentration b/a and the relative plate height h/b

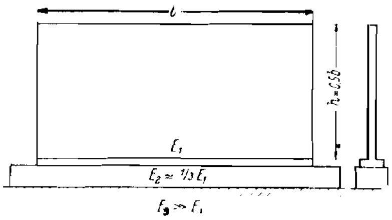

Fig. 29

Model of a wall plate with footing strip resting on an elastic foundation