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Concrete Walls in Compression Under Short-Term Axial and Eccentric Loads[1])

Murs en béton soumis à la compression sous chargements axiaux ou excentriques de courte durée

Betonmauern unter kurzzeitigem axialem Druck und exzentrischer Last

A. E. SEDDON, M. Sc., A. M. I. Struct. E., Garston, Watford

Introduction

This paper outlines the scope and principal results of an investigation of the strength of dense concrete walls at the Building Research Station of the Department of Scientific and Industrial Research. The walls were of types used in building construction and were cast monolithically in well-graded gravel concretes. A few data obtained from the earliest tests of the investigation were included in a previous paper to the Association [1], and the interim conclusions from these tests have been modified and extended by the subsequent work described in the present paper.

Axial Compression

Distributed loads

In tests on unreinforced walls of various heights up to 9 ft. and of thicknesses down to 2 in. the strengths of the walls in axial compression between stiff beams were not less than the "short column strength" of the concrete, i. e. they were not less than two-thirds of the cube strength. The effects on the wall strength of using hinges at the loaded edges instead of direction-fixed stiff beams were found to be insignificant for walls of height/thickness not exceeding about 30. The strength of the concrete was also found to have little effect on the relationship between the strengths of the wall and the cube

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for cube strengths ranging from about 2000 to 5000 lb. per sq. in. The typical mode of failure of walls of height/thickness not exceeding 30 consisted of primary shear (or sliding) along a plane inclined to one end of the wall and secondary crushing and horizontal tensile splitting resulting from eccentric compression in the part of the wall between the inclined plane and the far end of the wall. The primary shear (or sliding) generally occurred only at one end of the wall and resulted in a single shear segment, but on occasion two shear segments developed almost simultaneously at the two ends of the wall.

When the height/thickness ratio of the unreinforced wall was increased to about 50 there was no significant reduction of wall strength by reason of the increase in slenderness. Two alternative modes of failure occurred in successive tests, however. On the one hand crushing occurred in the manner observed on walls of smaller height/thickness ratios, and on the other hand buckling occurred. No strength reduction was evident when buckling occurred instead of crushing, and the test data suggest that height/thickness ratios of about 50 lie within the transition range between crushing and buckling failures. Horizontal deflections of the slender walls did not invariably indicate that failure would subsequently occur by buckling. In some cases a marked and gradual increase of the horizontal deflection occurred as the load was increased above about 85 per cent of the ultimate until the deflection amounted to half the wall thickness before buckling took place. In other cases, however, the deflection remained small until buckling occurred in one direction, or in both directions simultaneously.

Tests showed that for unreinforced walls of height/thickness not exceeding about 30 the height/length ratio was of primary importance in regard to wall strength. When the wall length was increased so that the height/length ratio was reduced below about 1.5, the wall strength increased to a marked extent. Values of wall strength as great as the cube strength of the concrete were observed for height/length ratios of 0.75 or less. This length effect on strength is attributed to shear restraint at the loaded edges of the wall, which induces biaxial compression in parts of the wall to an extent depending on the height/length ratio. As this ratio is reduced the incidence of biaxial compression increases and is accompanied by a strength increase. Some further observations on dimensional effects of this type are included in a recent paper by the author [2].

The strengthening effect on the wall of a single layer of mild steel reinforcement amounting to the quantity normally provided in concrete walls was found to be small. Tests performed in Sweden [3] showed a reduction of wall strength when a single layer of steel was included in thin walls, and this was attributed to a reduction in the quality of the concrete due to greater difficulty in placing and compacting the concrete. No strength reduction was observed in the Building Research Station tests and there was no evidence that including steel reduced the quality of the wall concrete. Walls containing

0.8 per cent vertical and 0.4 per cent horizontal steel in single layers developed strengths greater than the short-column strength of the concrete, and the contribution of the steel did not exceed the compressive yield strength of the vertical reinforcement. The yield load in the steel at failure of the reinforced walls did not exceed the deviation of the strengths of similar walls without steel above their mean strength.

When mild steel reinforcement was included in two layers near to the wall faces, however, an increase in wall strength greater than that to be attributed to the yield strength of the vertical steel was observed. Half-size model walls of height/thickness about 20 and with 0.4 per cent vertical and 0.2 per cent horizontal steel were tested between free hinges and their strengths amounted to the cube strengths of the concretes. Similar walls without reinforcement developed only two-thirds of the cube strength. This comparison suggests that with good workmanship and control two layers of light steel can result in a marked strength increase when the reinforcement is well tied together to form a cage. The phenomenon may be due to an increase of the effective strength of the concrete in compression due to lengthwise restraint by the horizontal reinforcement, comparable to the strengthening effect of increasing the length of the unreinforced wall.

Distributed axial compression tests on full-size and model walls with single door or window openings showed the important effects on wall strength of the manner of applying and distributing the compression over the wall length. Walls containing a central door or window opening of practical dimensions were axially loaded between stiff beams, and secondly by a beam and roller system to distribute the loading *uniformly* with minimum shear restraint. Owing to the practical difficulties of applying *uniformly* distributed load at both the top and base of a complete wall, this type of loading was applied to the top edges of models of parts of complete walls. The models included the top wall-beam and part of the wall-columns, i. e. the upper portion of the complete wall, and the special test assembly provided support for the wall-columns as provided by the remainder of the complete wall. Unreinforced and lightly reinforced walls were investigated in this fashion.

When unreinforced walls containing openings were loaded between stiff beams, beam action in the wall-beam above a door opening, or in the wall-beams above and below a window opening, caused serious tension cracks at low loads. The cracks quickly extended through the beam depth and redistribution of the load over the wall length resulted. As the load on the wall was increased, the effective eccentricity of the load on the wall-columns was reduced by redistribution and the load could be increased until the full axial compressive strength of the wall-columns was developed. Failure eventually occurred in a column along an inclined plane extending from a top corner of the wall to the adjacent corner of the opening, or from a point lower down the wall edge to a point within the depth and at the side of the opening. The ultimate load was in general about three times the load at which the wall-beam above a window opening was fully cracked, or as great as eight times the load causing full cracking of the wall-beam above a door opening.

Under the much more severe loading condition with the beam and roller system, cracking of the wall-beam resulted in failure of the unreinforced wall as a whole, since uniform distribution of the load over the wall length was maintained by the loading system. The ultimate load in these circumstances was therefore not greater than about one-third to one-eighth of that of a similar wall tested between stiff beams.

Further tests on lightly reinforced walls of the same dimensions showed that small quantities of reinforcement in the wall as a whole and the reinforcement around openings recommended in British Standard Code of Practice 111: 1948 [4] were sufficient to restrain cracking of the wall-beam and allow the wall-columns to develop their full axial compressive strength under uniformly distributed compression. When light steel was included, failure eventually occurred with evidence of some eccentricity of the loads in the wall-columns, but the loads in the columns at failure were sensibly equal to their crushing loads in axial compression.

Concentrated loads

The effects of axial load concentration were investigated by tests on full-size 4 in. walls of storey height and a length of 6 ft. Concentrated loads were applied to the top edges of the walls with the walls supported over their full length by a stiff beam. The loads were concentrated centrally over the full wall thickness using adequately stiffened loading plates of various lengths. The length of wall over which the load was concentrated was varied from one-twelth to one-half of the total wall length, and tests were performed on unreinforced walls and on similar walls containing small quantities of horizontal mild steel reinforcement.

Data obtained from the tests on unreinforced walls are represented in

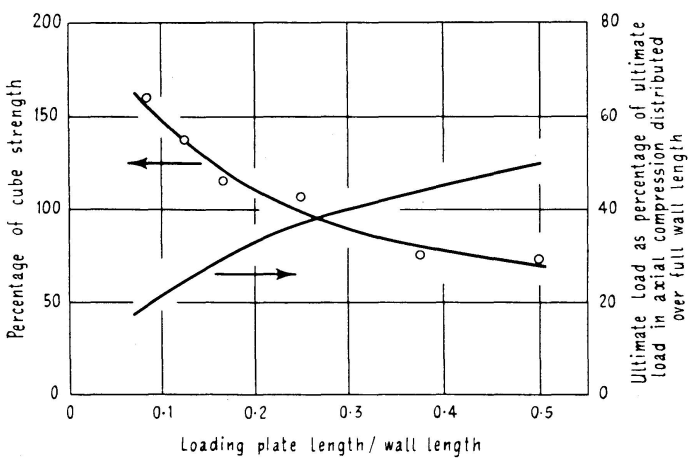

Fig. 1. Strengths of unreinforced concrete walls under concentrated axial loads.

fig. 1 and it may be seen from the figure that failure of the walls occurred at applied mean stresses beneath the loading plates which ranged from 160 to 73 per cent of the 4 in. cube strengths of the wall concretes. When the load was concentrated over half the wall length the ultimate mean stress beneath the plate was therefore about equal to the strength of the wall in distributed axial compression with the load applied through stiff beams over the full wall length, i. e. the ultimate load was about one-half of the ultimate load in the latter case. It is to be concluded that for greater lengths of loading plate the ultimate mean stress beneath the plate remains constant and the ultimate load increases in proportion to the loaded length.

With the load concentrated over small proportions of the wall lengths, vertical splitting through the full wall height and local crushing of the concrete beneath the plate occurred at failure. In these tests the splitting due to horizontal tension and the local crushing occurred almost simultaneously, but as the length of the plate was increased splitting tended to occur first. When the plate length was half the wall length, splitting occurred first at a mean stress beneath the plate of about two-thirds of the cube strength, and the load could be increased further to the ultimate load causing local crushing and a mode of failure which was intermediate between that observed for short plate lengths and that observed with the load fully distributed.

Walls of the same dimensions but containing 0.4 per cent horizontal mild steel distributed equally over the wall height were tested for comparison. With the load concentrated over a short plate length the vertical splitting was restrained and did not extend down to the base of the wall, but local crushing of the concrete again occurred at an ultimate load that was no greater than the corresponding ultimate load for the unreinforced wall. Consequently, the tests showed the need for special reinforcement of the wall near to the loading plate if the resistance of the wall to local crushing is to be increased.

Eccentric Loading

In the eccentric loading tests models of 4 in. and 6 in. walls to scales of 1 : 2 and 1 : 3 were tested between hinges with various initial eccentricities of the load up to five-twelfths of the wall thicknesses. The 2 in. and 3 in. models were 4 ft. 6 in. high and 3 ft. long, and the hinges were arranged to induce compression with bending in single curvature. The hinges were 5 ft. 3 in. apart, so that the effective height/thickness ratios of the models were 20 and 30. The concretes were similar to those used in the axial compression tests described previously, and tests on models having vertical and horizontal mild steel reinforcement were included. Earlier tests to compare the strengths of unreinforced models of the same dimensions with those of full-size prototypes showed that scale effects in the models were small.

Unreinforced walls

Tests showed that the axial compressive strengths of the unreinforced models amounted to about two-thirds of the cube strengths of the concretes. The strengths of the models with various initial eccentricities are shown in fig. 2, together with curves given by theoretical analysis assuming that the curvature of the eccentrically loaded wall does not increase under load to a sufficient extent to cause an effective increase of the eccentricity. The compression curve showing values of $1/\left(1+\frac{et}{2k^2}\right)$, where e is the initial eccentricity, t is the wall thickness and k is the radius of gyration of the wall section about central axes parallel to the wall length, is given by elastic analysis assuming the failure occurs at a limiting compressive stress equal to the wall strength in axial compression. The upper compression curve is obtained similarly with the assumption that the limiting compressive stress is $33\frac{1}{3}$ per cent greater than the axial strength. The tension curve of the figure is given by elastic analysis for tension failure at a limiting tensile stress equal to one-eighth of the cube strength of the concrete, i. e. three-sixteenths of the axial strength.

The unreinforced wall data are compared with different theoretical values in fig. 3, and in this case the theoretical values are those given by elastic analysis with allowance for increasing curvature under load. The curves are given by calculation assuming sinusoidal deformation of the wall, an elastic modulus of 1200 times the cube strength of the concrete, compression failure with small initial eccentricities at a limiting compressive stress equal to the axial strength, and tension failure with large initial eccentricities at a limiting tensile stress equal to 18 per cent of the cube strength (being the value of the limiting tensile stress giving closest agreement with the measured strengths).

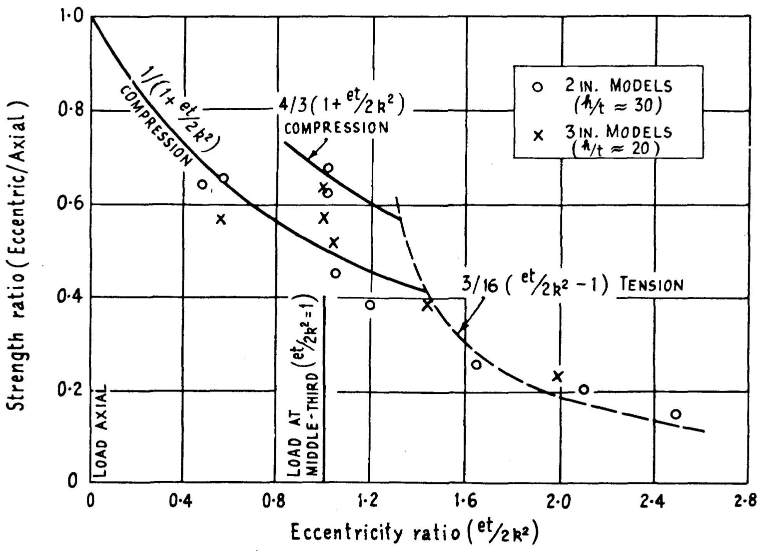

Fig. 2. Strengths of unreinforced concrete walls under eccentric loads, and theoretical relationships neglecting increasing curvature under load.

It may be concluded from figs. 2 and 3 that compression failures occurred for small initial eccentricities up to about one-tenth of the wall thicknesses at loads intermediate between calculated ultimate loads obtained by neglecting increasing curvature and allowing for it in the above manner, with the assumption of a limiting compressive stress equal to the axial strength of the wall. A pronounced scatter of results was observed for larger initial eccentricities of about one-sixth of the wall thickness, and this may be attributed to a transition stage between compression and tension failures. The upper limit of the range of strength observed for these eccentricities corresponded approximately with calculation neglecting increasing curvature and the assumption of compression failure at a limiting stress $33\frac{1}{3}$ per cent greater than the axial strength. The lower limit of the range agreed with calculation including allowance for increasing curvature and assuming compression failure at a stress equal to the axial strength. For the largest initial eccentricities of the tests, tension failures occurred at loads that were in good agreement with calculated values including allowance for increasing curvature and assuming a limiting tensile stress of about one-fifth of the cube strength. Reasonably close agreement was obtained, however, between the measured strengths and calculated values given more simply by neglecting increasing curvature and assuming tension failure to occur at a stress of one-eighth of the cube strength.

Reinforced walls

Similar tests were performed on 3 in. models containing 0.4 per cent vertical and 0.2 per cent horizontal mild steel divided equally in two layers near to the wall faces. The layers of steel were well tied together and the ends of the vertical bars were specially treated to give plane contact with the hinged loading beams. The concretes of the walls had 4 in. cube strengths of about

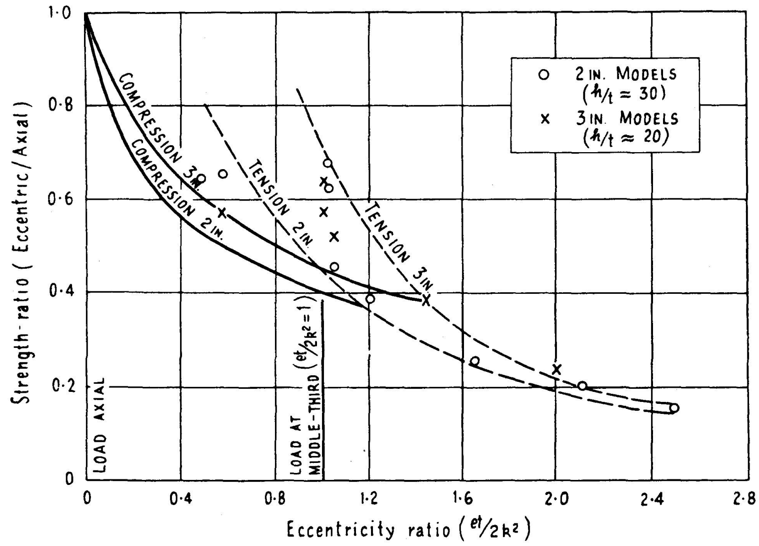

Fig. 3. Strengths of unreinforced concrete walls under eccentric loads, and theoretical relationships including increasing curvature under load.

3500 lb. per sq. in. in general, and the steel yield strength ranged from about 40000 to 45000 lb. per sq. in.

The axial compressive strengths of the reinforced walls amounted to the cube strengths of the concretes when calculated simply by dividing the ultimate loads by the horizontal cross-sectional areas of the walls ignoring the small areas of vertical steel. These strengths are to be compared with axial strengths of two-thirds of the cube strengths for similar walls without reinforcement, i. e. they indicate a 50 per cent increase in axial strength due to the steel content.

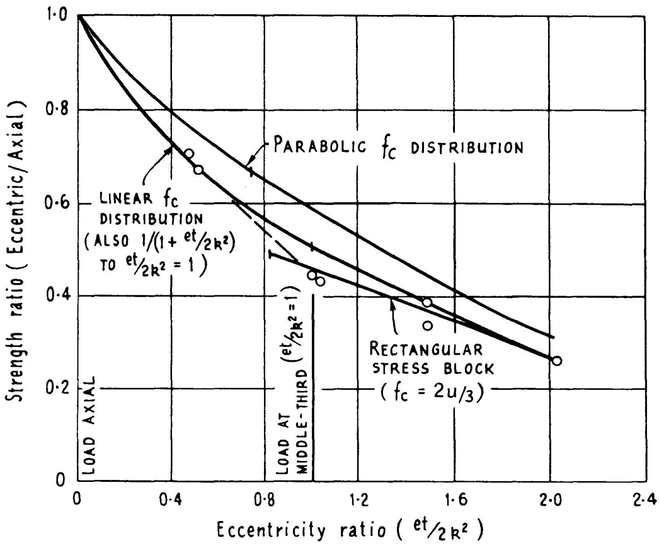

Fig. 4. Strengths of reinforced concrete walls under eccentric loads.

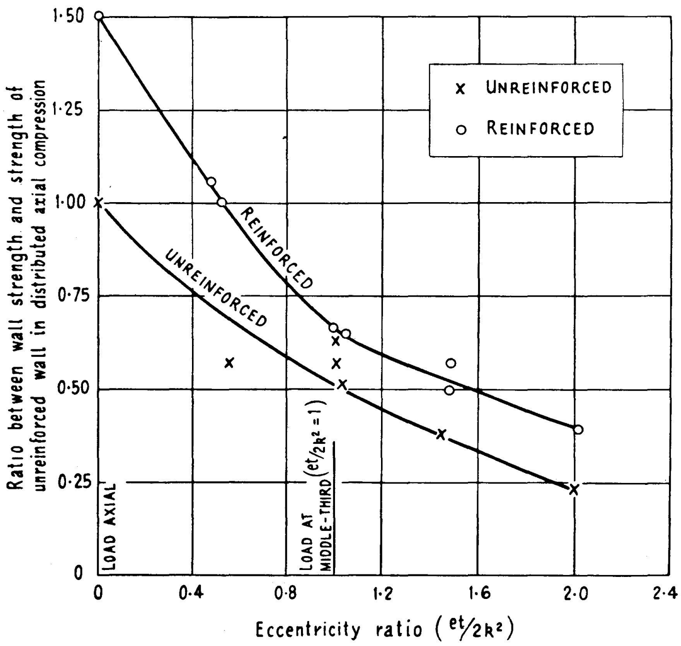

Fig. 5. Comparison between strengths of reinforced and unreinforced concrete walls under eccentric loads.

The reinforced wall strengths for various initial eccentricities are shown in fig. 4 in relation to their axial strengths, and in fig. 5 in comparison with the strengths of similar walls without steel under the same eccentricities of load. Curves are included in fig. 4 to indicate calculated values with various assumptions. An assumption common to all the curves is that the concrete cannot resist tension. The upper curve is given by calculation assuming that the compressive stress in the concrete in compression is distributed parabolically to a maximum equal to the cube strength of the concrete and the modular ratio is 7. The intermediate curve is calculated by assuming a linear distribution of the compressive stress to the same maximum and a modular ratio of 15. The discontinuity marked on the upper curve denotes the conditon for which the theoretical neutral axis is at the tension face, while the division marked on the intermediate curve indicates the limit of the left-hand portion of this curve which sensibly coincides with values of $1/\left(1+\frac{et}{2k^2}\right)$. The lower line of the figure is given by calculation assuming a rectangular stress block for the concrete in compression, of depth amounting to two-thirds of the cube strength, and assuming that for positions of the neutral axis lying between the two layers of steel the tension and compression layers develop a yield strength of 40000 lb. per sq. in.

Fig. 4 shows good agreement between calculation with the rectangular stress block assumption and measured strengths for initial eccentricities equal to and greater than one-sixth of the wall thickness. The linear distribution curve and values of $1/\left(1+\frac{et}{2k^2}\right)$ agree with measured values for eccentricities of about one-twelth of the thickness, and the broken line of the figure indicates an apparent transition stage for eccentricities between about one-twelth and one-sixth of the thickness. The uppermost curve over-estimates the wall strengths throughout the range of eccentricities investigated, while the other two curves become coincident around an eccentricity of one-third of the thickness.

The comparison shown in fig. 5 illustrates the strength increases provided by the steel for various initial eccentricities. These increases fluctuated about the value of 50 per cent observed for axial loading and were smallest for eccentricities of about one-sixth of the wall thickness. These eccentricities lie within the transition ranges separating compression and tension failures for the two types of wall and for which greater scatter of measured strengths was observed.

Conclusion

The tests outlined in the paper show that, with good workmanship and careful alignment of the applied loads in the laboratory, the strengths of thin walls of dense concrete are considerable when loads are applied axially. The height/thickness ratio can be increased to a high value without a sensible reduction in strength, and the strength may be increased by increasing the wall length above a defined limit. Alternative modes of failure for height/thickness ratios of about 50 have little effect on the strength when the wall is flat-ended under test, and for height/thickness ratios up to about 30 crushing failures occur even if the loaded edges are free to rotate under load.

Two layers of light steel reinforcement can result in a marked increase in strength under axial loads. When the wall contains an opening the reinforcement of the wall-beam or beams is of prime importance, and light steel can make an important contribution to strength according to the distribution of load on the wall. This steel can allow the development of the full strength of the wall columns if it is provided in the wall-beams.

Investigation of the effects of load concentration in axial compression showed that the ultimate mean applied compressive stress under the load ranges from about 160 per cent of the cube strength of the concrete for loads concentrated over only a small part of the wall length to about two-thirds of the cube strength for loads concentrated over half the wall length. When the load is more widely distributed, the ultimate mean stress remains constant at about two-thirds of the cube strength, and the ultimate load varies in proportion to the length over which the load is distributed. Light steel horizontal reinforcement distributed equally over the wall height is ineffective as a means of increasing the wall strength under concentrated loads.

The eccentric loading tests determined the strength reductions that occur with increasing initial eccentricity of the load when the wall is unreinforced and when it contains small quantities of reinforcement. Good agreement with selected methods of calculating the wall strength were obtained, and an indication is given of the contribution to strength of the reinforcement.

Acknowledgement

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Summary

The paper describes a laboratory investigation of the behaviour of thin walls of types employed in building construction. Tests were performed on full-size walls and model walls and loads were applied over all or part of the wall length to include cases of distributed and concentrated loads. Information is given on the effects on wall strength of varying the slenderness ratio and length of the wall, the strength of the concrete, the eccentricity and concentration of the applied load, and on the contribution of reinforcing steel to wall strength.

Résumé

L'auteur expose ses recherches de laboratoire sur le comportement des parois minces. Il s'agit ici d'un type de paroi qui est employé, en construction, pour le contrôle au cours des essais de destruction de courte durée.

Les essais ont été effectués sur des parois réelles aussi bien que sur des modèles. Les charges ont été appliquées sur toute la longueur de la paroi ou sur une partie seulement de cette longueur, afin de faire intervenir des charges réparties et des charges concentrées.

L'auteur donne des indications sur le comportement des parois:

a) En fonction de la finesse et de la longueur de la paroi.
b) En fonction du dosage du béton.
c) En fonction de l'excentricité et de la concentration des charges appliquées.
d) En fonction de l'effet de décharge obtenu par incorporation d'armatures en acier à haute résistance.

Zusammenfassung

Der Bericht beschreibt die Erforschung des Verhaltens von dünnen Wänden im Laboratorium. Es handelt sich dabei um einen Wandtyp, wie er im Hochbau zur kurzfristigen Zerstörungsprüfung verwendet wird.

Die Versuche wurden an naturgetreuen sowie an Modellwänden vorgenommen. Die Lasten wurden über die ganze Wandlänge oder nur auf Teile der-

selben aufgebracht, damit verteilte und konzentrierte Lasten in den Versuchen eingeschlossen waren.

Es werden Angaben gemacht über die Wirkung der Beanspruchung von Wänden:

a) In Funktion des Schlankheitsgrades und der Länge der Wand.
b) In Funktion der Dosierung des Betons.
c) In Funktion der Exzentrizität und Konzentration der aufgebrachten Belastungen.
d) In der Entlastung der Wandbeanspruchung durch Verwendung von hochwertigem Stahl.