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Model tests on shear walls composed of prefabricated concrete elements

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1. INTRODUCTORY REMARKS

The model tests of prefabricated shear walls were undertaken at the Norwegian Building Research Institute. Three models were investigated under vertical and horizontal loads. Each model was composed of 14 concrete elements with an overall dimension of 1,50 x 3.76 m in scale 1 : 10. A shear-key type vertical mortar joint existed in each model along the centre axis of the wall. Two of the models had no openings whilst the third one was weakened by two rows of door-openings situated symmetrically about the centre line of the wall.

The models were subjected vertically to a constant uniformly distributed load of 40 tons. The horizontal uniformly distributed load was increased from zero to about 10 tons.

The object of the tests was:

a) to investigate the behaviour of prefabricated shear walls by means of models with as great similarity to real walls as possible.
b) to verify the calculation methods on elastic and structural homogenity of the wall.

The following subjects were of special interest:

The stress distribution along the restraint part of the wall and in the vertical joint. This was obtained by means of strain gauge rosettes. The deformability of walls - the deflection curves of the top of the wall and of the structure as a whole. The appearance of cracks and their effect on the wall.

2. CALCULATION OF TESTED WALLS

The wall without openings was calculated by using simplified formulae of mechanics. The Rosman method was employed for the wall with openings. In addition both model types were solved by computation programme based on the Finite Element Method and on frame analysis method. The wall with openings was calculated by a version of the Finite Element Method considering the wall as a two-dimensional structure and also by a frame analysis programme were the wall is regarded as a plane structure consisting of columns and horizontal beams.

When the Finite Element Method is used, the wall is divided in 224 triangular elements above the foundation. The elements have one point in each corner and two points on each side where forces are acting. Each point has two forces — one in the x-direction and one in the y-direction. For each point in the structure two equations are established — for forces in the x-direction and forces in the y-direction. This makes a set of equations with two unknown factors each. When the equations are solved, the movements of the points in x- and y-direction will be known. From this, the stresses can be calculated. The theoretical model for these calculations is shown in *fig. 1*.

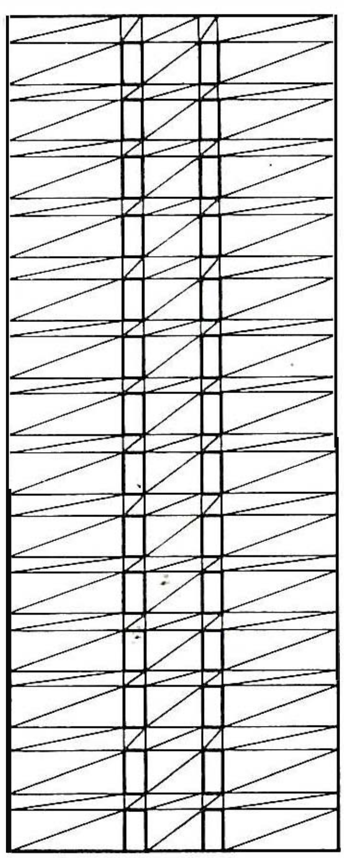

Fig. 1. Model used for calculating the shear wall with openings by Finite Element Method. The model is divided in 224 triangular elements.

The frame analysis programme calculates the wall as a plane structure, taking into account the deformations caused by moments, shear forces and normal forces. Theoretically, the horizontal beams are running between the center lines of the columns, but to get a deformability which is closer to the original model, the ends of the horizontal beams are considered to be infinitely stiff. These rigid sections are shown in *fig. 2*. From these calculations, the displacements, the vertical stresses along the restraint section and the shear stresses along the vertical joint are found and presented in *fig. 3–6*.

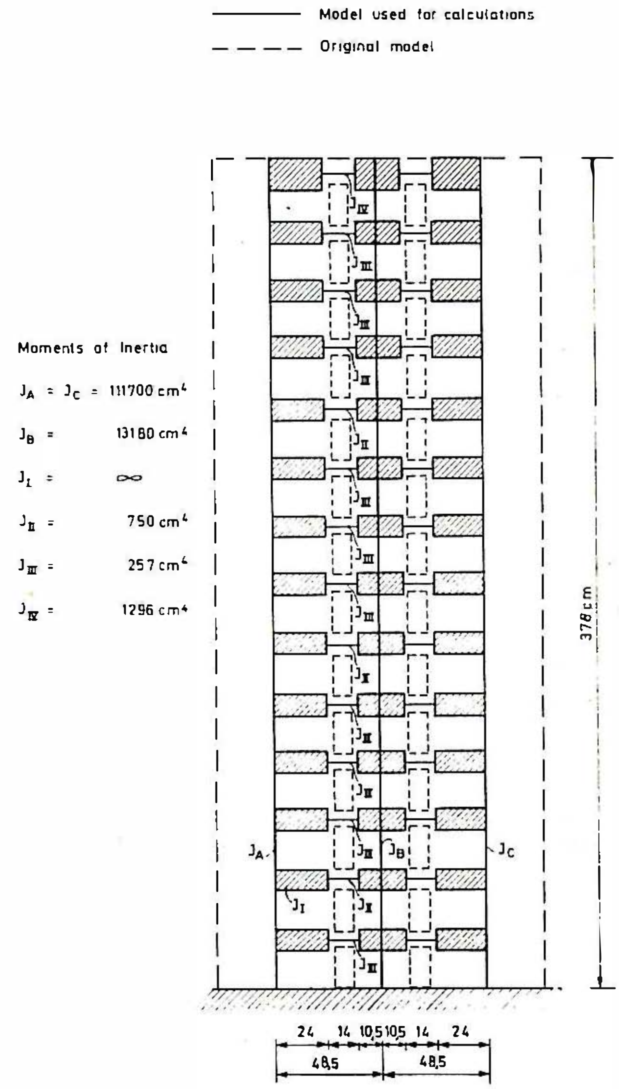

Fig. 2. Model used for calculating the shear wall with opening as a frame.

3. TEST RESULTS AND THEIR COMPARISON WITH THEORETICAL DATA

3.1 Shear stresses in the vertical joint

Shear stresses along the center line of the wall from the calculations mentioned above are presented in *fig. 3 and 4*.

The stresses found from the calculation by the Finite Element Method on the wall with openings need special explanation. The stresses are much higher at the openings than at the level of the horizontal beams. From theory of elasticity it is known that such a variation should appear. However, the applied version of the Finite Element Method is not the most suitable method when the stresses are changing rapidly. The division of the wall into elements is far too rough for the magnitude of the stresses to be reliable. But the curve shows that a variation clearly exists, even if it does not tell anything about the numerical value of the maximum and minimum stress.

The curve calculated by means of the frame analyses programme is more reliable. This curve is compared with the one from the calculations with the Finite-Element Method in *fig. 4*. The agreement between the macimum values from the two methods is quite good.

The shear stresses calculated by the Finite Element Method for the wall without openings are also presented in *fig. 4*. The stresses are smaller than the stresses found by the other calculations.

The measured shear stresses from the wall without openings are plotted on the same figure. The curve lies mainly between the curves calculated for the wall without openings and the wall with openings. It has about the same maximum value as the theoretical curves, but the position of the maximum shear stress is different. The position of the maximum stress appears much higher above the foundation than that obtained by calculations.

There is a remarkable difference between the measured shear stress close to the foundation and the calculated values. One reason can be that a crack appears in the lowest horizontal joint at an early stage. The effect of such a horizontal crack in the tension side of the wall has been simulated by the Finite Element Method.

By these calculations it has been possible to approach the curve for measured shear stress, but the calculations also show that a horizontal crack can not be the only reason.

The three axial strain gauges situated directly on both sides of the vertical joint of the model without openings gave a good agreement between the directions of the normal principal stresses established experimentally and theoretically. Under the action of horizontal loads the increase in stresses measured by skew situated gauges,

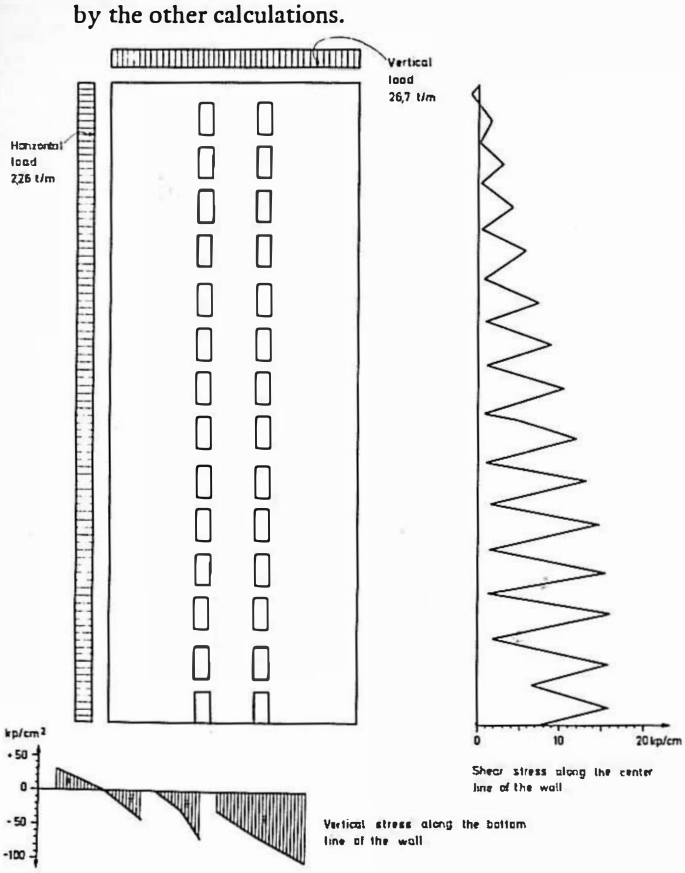

Fig. 3. Stresses in a shear-wall with openings calculated by the Finite Element Method.

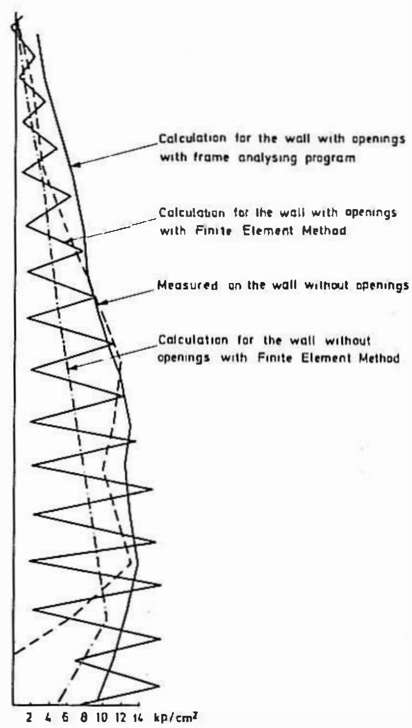

Fig. 4. Shear stress in the center line of the wall.

parallel to the diagonals of keys, were noticed. The deformations of the diagonals of keys were of opposite signs. After releasing the horizontal loads, the compressive deformations have more or less returned to their initial values. The tensile deformations in some keys were of a plastic character. This could be a reason why the shear stresses at these points evaluated from these deformations were overestimated. Generally, these measurements indicated that the statical conditions of the vertical joint is changeable. In the first steps of loading the joint behaved like an appropriate strip of cast in situ structure (*fig. 5d*). With further increase in stresses, the tendency towards the conditions in *fig. 5e* were observed.

It is remarkable that in the area of maximum shear stress in the joint, i.e. the middle part of the joint, tensile deformation of the steel bars crossing the space of the joint, was noticed. This deformation did not vanish completely when the wall was unloaded.

3.2 *Stresses in the restraint section of the models*

The stresses measured in the restraint section of *the models without openings* (models I and II) were in a good agreement with the theoretical values, especially for smaller horizontal loads, H < 6 tons. Tensile stresses, due to a simultaneously acting vertical load, at this value of H, did not appear.

For higher values of the horizontal load two characteristic features of the wall behaviour were observed:
first – model I, cracked (succesively) in two bottom horizontal joints,
second – model II, did not crack because of the epoxy resin mortar partly applied in the bottom joints.

The result of crack formation was the marked increase in stresses in the compressive area of the horizontal section. The strain in the tensile area of the section did not disappear after cracking, but it settled around the ultimate values.

The stress curves for the uncracked model showed that the whole wall behaved like a homogeneous cantilever beam and not like two separate cantilever beams.

The vertical stress along the restraint section measured on the *model with openings* and the stresses calculated by theoretical methods are presented in *fig. 6*. The curves represent the values found with 40 tons vertical load and 10 tons horizontal load uniformly distributed along the upper edge and one side of the wall.

The discrepancies in the results of the calculations done by the Finite Element Method, by the frame analysis programme and by the Rosman method are very small. The measured values, however, differ from the

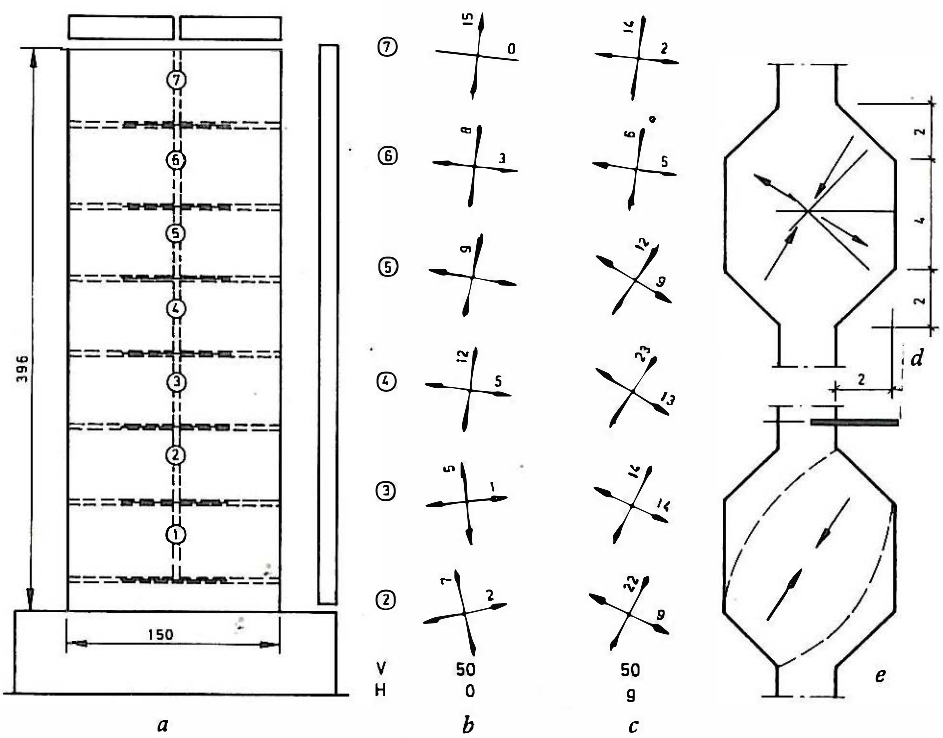

Fig. 5.

calculated ones. It seems as if the tested wall is acting more like a rigid plate than assumed by the calculations.

The measured values were in better agreement with the theoretical ones in the compressive area of the section, where the concrete was further compressed under horizontal loads.

The formation of cracks in the connecting beams at H = 3–4 T did not cause any visible increase in stresses in the horizontal sections of the model.

3.3. Deflection of models

The deflection at the top of the models without openings is in good agreement with the calculated values.

The theoretical curves are based on an assumption of Youngs modulus being equal to 2.5×10^5 kp/cm^2 resp. 2.1×10^5 kp/cm^2 for model I and II. These values were found from concrete test cylinders made of the same concrete as the models.

The deflection curve for the model should be non-linear because of the non-linearity of the deflection curve for concrete under compression. With the chosen values for Youngs modulus, the theoretical deflection curves are crossing the empirical curves at an horizontal load of about 11 tons for model I, and about 8.5 tons for model II.

The deflection curves calculated by simple elastic theory are close to those calculated by the Finite Element Method, even though the ratio H/B for the wall is 2.5. For higher H/B-values, it is obviously sufficient to consider the wall as a cantilever beam when deflections are calculated.

The deflection curves for the model with openings, indicated an almost linear increase in the deflection for small horizontal loads, $H < 4–5$ t, and a non-linear increase for greater loads. These deviations could be explained as the effect of the crack formation in the corners of the connecting beams.

It should be added here that the deformation line of the foundation was quite different in the case of walls without openings and walls with openings. In the first case, when the wall is set on the basement like that in *fig.5a*, the restraint section of the wall rotates and remains almost plane. In the second case due to non plane stress distribution, see *fig. 6*, the outer cantilevers rotate more than the middle one. In such a case the deflection of a particular wall cantilever, with respect to the restraint sections, can be of a different value even though the wall remains as a continuous structure.

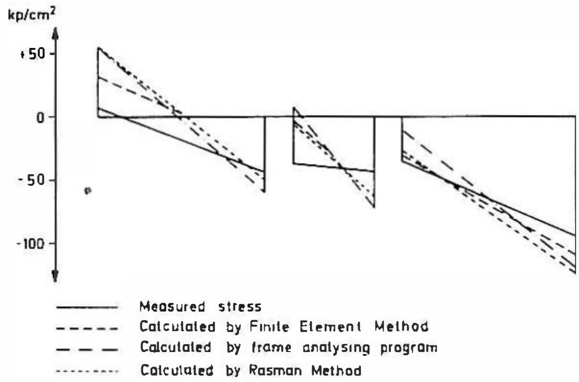

Fig. 6. Vertical stress along the fixing section.

4. CONCLUSIONS

The tests carried out indicated that the prefabricated wall with mortar joint of the shear-key type and with dimensions as indicated in *fig.5d* (multiplied by a model similarity factor s = 10), behaves like a homogeneous structure as long as the cracks in the lowest horizontal joint do not appear.

The changes fo the statical conditions of the vertical joint, for higher values of shear stress ($\tau > 10$ kp/cm^2) do not change the wall into a multi-cantilever structure. For small shear stresses, the friction between mortar in the joint and the concrete of the prefabricates, and the fixing of the wall at the basement are factors that limit the shear deformability of the joint in a real wall. These factors are not considered, when the joint deformability is tested under direct shear loads.

For the calculation of the deflection of the prefabricated wall the E modulus can be assumed constant. The possible reduction of this value, when considering the deformability of horizontal joints, must be proved by testing of particular joints.

The lowest horizontal section joint of the prefabricated shear wall is the most vulnerable part of the wall due to shear forces. The appearance of tensile stresses at one of the edges of the wall might introduce considerable changes in the statical behaviour of wall.

The tests did not explain the state of stresses in a vertical joint near the restraint section. It seems that the stresses at this point are of less importance when considering the behaviour of the whole structure.

The foundation of the wall, supposed to be a rigid one, should also be considered as deformable. Its deformation causes an additional rotation of the supporting section of the prefabricated wall.

The tests confirmed the statical condition of the wall as a multicantilever and the calculation method derived by Rosman for walls with opening rows. Other adequate calculation methods are the frame analysis method or the Finite Element Method, the latter not for results obtained for the restraint section.

The cracks of the prefabricated shear wall with opening rows might first appear at the restraint section or in the corners of the connecting beams, but not in the vertical joint. In case of cracks which occured in lower situated connecting beams, their effect on the behaviour of the wall should be observed. The appearance of cracks only caused the redistribution of shear forces along the line crossing the connecting memebers.

SUMMARY

Model tests on shear walls subjected to vertical and horizontal loads have been carried out. The purpose of the tests has been to study the stress distribution in shear walls with mortar joints and the effect of vertical rows of openings.

Three models with dimension 150 x 376 cm, each composed of 14 elements, have been tested. One wall had two vertical rows of openings, the others were without openings. In each model a vertical joint of the shear-key type was located along the centre axis of the wall. The results of the model tests have been compared with different calculation methods. With exception of the shear stress in the lower part of the vertical joint good agreement has been found. The reason for the discrepancies have been discussed. The tests indicated, that the vertical and horizontal joints did not have any special effect on the deformability and state of stress of prefabricated walls.

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