THE INFLUENCE OF FREQUENCY ON THE SHEAR STRENGTH AND DUCTILITY OF MASONRY WALLS IN DYNAMIC LOADING TESTS

by

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SYNOPSIS

Horizontal cyclic-loading tests at various frequencies up to 5 c/s were carried out on a series of wall elements made of hollow building-blocks with expanded-clay aggregate. H-δ diagrams and hysteresis loops were obtained. It was found that the wall's dynamic shear strength $(H_{max})_{dyn.}$ increased with frequency ν according to the formula:

$$(H_{max})_{dyn.} = (H_{max})_{stat.} \left\{1 + \frac{3}{100} \cdot \nu\right\},$$

$(H_{max})_{stat.}$ being the shear strength of the wall under static loading. Neither the initial stiffness of the wall nor its displacement at maximum load or its ductility were significantlyaffected by frequency change.

1.0 INTRODUCTION

After the Skopje, Yugoslavia earthquake of 1963 investigations into the shear strength of wall elements subjected to static combined (vertical/horizontal) loads, representing seismic loads, were begun at the Institute for Research and Testing in Materials and Structures (ZRMK), Ljubljana. From the results of these tests the main material-technical characteristics of the wall elements were determined. The same failure mechanism was obtained as had been observed on the walls of buildings in Skopje.

In order to get a better insight into the dynamic behaviour of structures, special laboratory equipment for the carrying-out of dynamic seismic tests on model structures [1] was set up at ZRMK in 1969. Later on equipment for the testing of fullscale structural elements, fixed between two horizontal surfaces, was added (see Fig.1). With all this equipment it is possible to carry out dynamic tests on full-size and model wall elements, as well as on model masonry buildings. Such tests provide a basis for the more economic design of masonry buildings in seismic regions.

Seismic loads on wall elements are applied, for simplicity, in the form of a "block-diagram", where the frequency of cyclic loading is one important piece of input data. The natural frequencies of ordinary masonry buildings lie in the range 1.0 - 5.0 c/s. However it would be desirable that laboratory seismic tests on wall elements be carried out at one particular frequency in order to improve comparability between test results. For this reason it was decided that tests on as near as possible identical wall elements should be carried out at frequencies in the range 0.02 - 5.0 c/s in order to determine the influence of frequency on their material-technical characteristics.

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2.0 DESCRIPTION OF TESTS AND ANALYSIS OF RESULTS

A total of fifteen walls were tested. They were made of hollow lightweight building-blocks of expanded-clay aggregate and good-quality PFA-lime-cement mortar, and were lightly-reinforced in every other horizontal mortar joint. The walls were 1.0 m wide, 1.5 m high and 0.2 m thick.

Dynamic shear-strength tests at frequencies of 1.0, 3.0 and 5.0 c/s were carried out on a total of nine walls, five walls were tested "statically" at a frequency of 0.02 c/s, and one wall was tested under axial vertical load. In the shear-strength tests the walls were held under a constant vertical load of 15 Mp ($\sim$150 MN) between two horizontal surfaces kept permanently parallel, thus only allowing horizontal and vertical movement of the upper surface with respect to the lower one. Such a vertical load corresponds to a normal stress of 8.0 kp/cm2 (0.8 N/mm2), which is approximately a quarter of the failure stress under axial vertical load.

The dynamic horizontal loading, which consisted of programmed sinusoidal displacements in the form of a block-diagram, was applied by means of two jacks, one of which was connected via an automatically-regulated valve to a high-pressure oil-pump. The valve was controlled by an electrical signal from the tape-recorder, on whose track the desired loading program had been previously recorded. The tests were split up into several phases. In each phase horizontal displacement was increased in ten equal steps to a maximum value $\pm \delta_f$. At each step five sinusoidal cycles were carried out. In this way the block-diagram was reproduced (see Fig.2). The maximum displacements in the four loading-phases were 2, 5, 10 and 20 mm.

The shear force in the wall was measured by means of dynamometers and the relative displacement of the upper and lower surfaces with inductive measuring devices. At the same time hysteresis loops were drawn on an x-y graphical recorder. From these, shear-force/displacement H-δ diagrams were constructed for each wall (see Fig.3). Each point on the H-δ diagram represents the moment of maximum displacement in the cycles at one particular step in the block-diagram. The following test results can be seen in the H-δ diagram:

- H_{max} - the shear strength of the wall,
- K_o - the initial stiffness of the wall,
- $\delta(H_{max})$ - the displacement at which H_{max} is reached.

The theoretical elastic displacement of the wall at load H_{max} is given by $\delta_o = H_{max}/K_o$. Ductility is defined by the expression $D = \delta(H_{max})/\delta_o$. The results of the tests are shown in Table 1. The shear modulus of the walls varied from 2000 to 3500 kp/cm^2, according to their initial stiffness. The reference shear strength of the unreinforced wall τ_k was 2.6 kp/cm2. The average compressive strength of the building blocks used was 65 kp/cm2, and of the mortar 55 kp/cm2. From the results of the vertical axial loading test the compressive strength of the wall was found to be 44 kp/cm2. Elastic and deformation moduli of 45,000 and 40,000 kp/cm2 were obtained at one-third of maximum load.

In Fig 4 the wall's shear-strength H_{max} is plotted against frequency ν. It can be seen from the diagram that there is a significant increase in shear-strength when the frequency of cyclic-loading is increased from

0.02 c/s ("static" tests) via 1.0 and 3.0 c/s to 5.0 c/s ("dynamic" tests). Assuming a linear increase in shear-strength with frequency a straight line was plotted through the points by means of the method of least squares. The equation for this line can be written as follows:

$$(H_{max})dyn. = (H_{max})stat. \left\{1 + \frac{3}{100} \cdot \nu\right\}$$

It is valid for the range $0 < \nu \leq 5.0$ c/s. The correlation coefficient r is 0.75, with a total of 14 points. It can be shown statistically that with 90%-probability r lies in the range $0.45 \leq r \leq 0.90$. The above equation indicates an increase in shear-strength of 3.0% if loading frequency is increased from 0.02 to 1.0 c/s, one of 9.0% if it is increased from 0.02 to 3.0 c/s and one of 15.0% if it is increased from 0.02 to 5.0 c/s.

From Table 1 it can be seen that the changing of loading frequency has no clearly significant influence on the initial stiffness of the wall K_o, or on the displacement $\delta(H_{max})$ or ductility D.

3.0 CONCLUSIONS

1. In the dynamic frequency range 1.0 - 5.0 c/s it was found that the shear-strength of the tested wall-elements increased by 12% when loading frequency was increased from 1.0 to 5.0 c/s. The shear-strength of walls tested at a frequency of 1.0 c/s was approximately the same as that of wall tested "statically".
2. The changing of loading frequency had no clearly significant influence on the initial stiffness of the wall nor on the displacement corresponding to the moment when the shearstrength of the wall was reached, nor on the ductility of the wall. The values of these characteristic quantities varied considerably even at the same frequency.
3. The results of the tests show that if dynamic tests are to be carried out a single loading frequency can now be chosen for further tests. A frequency of 1.0 c/s is proposed.

BIBLIOGRAPHY

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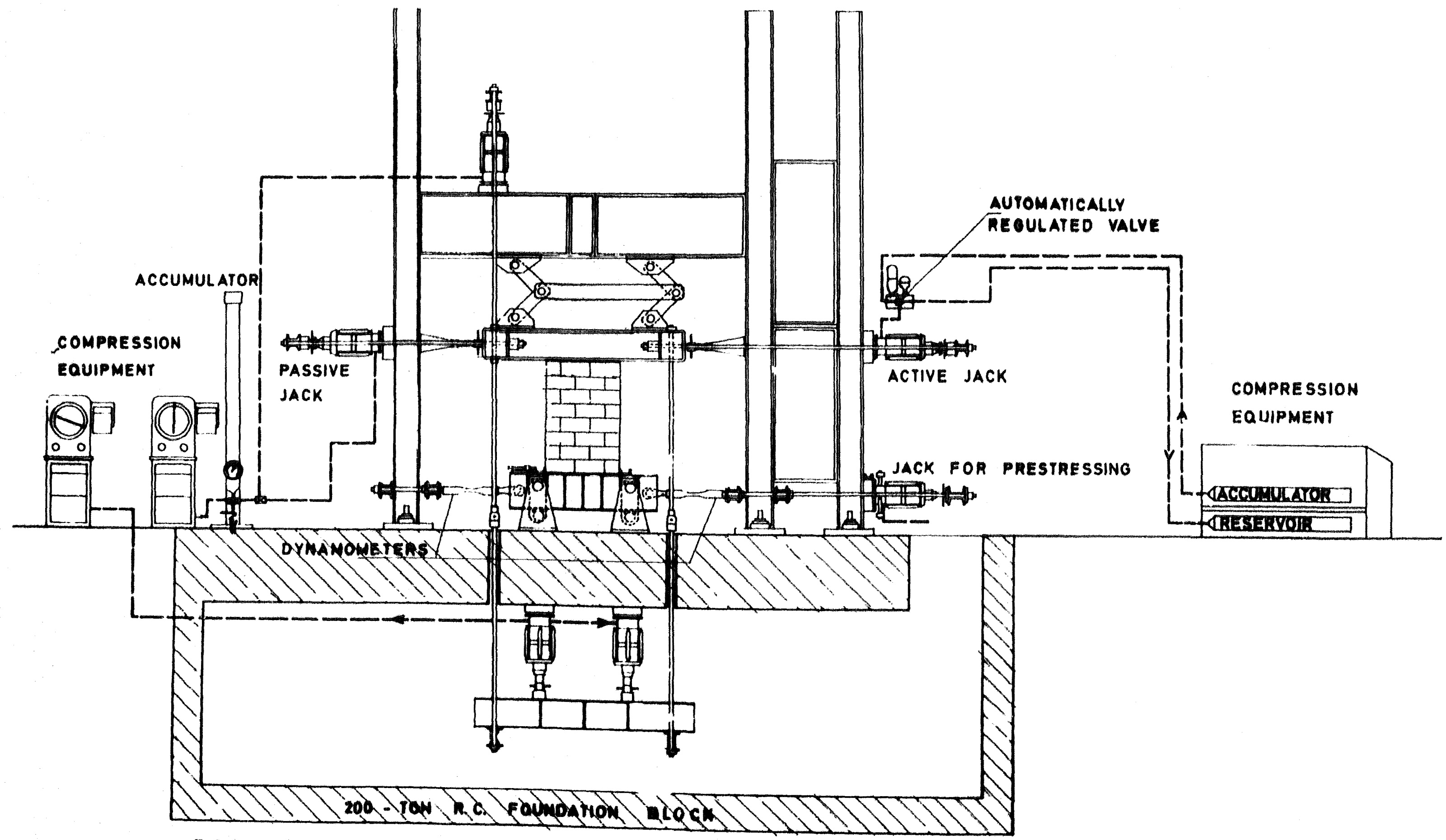

FIG 1 : SEISMIC TESTING EQUIPMENT FOR WALL ELEMENTS

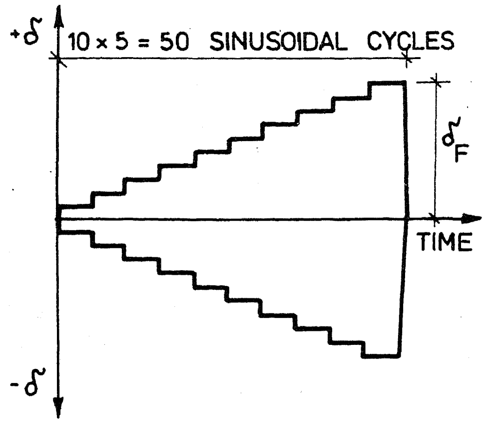

FIG. 2 : BLOCK - DIAGRAM FOR TYPICAL LOADING PHASE

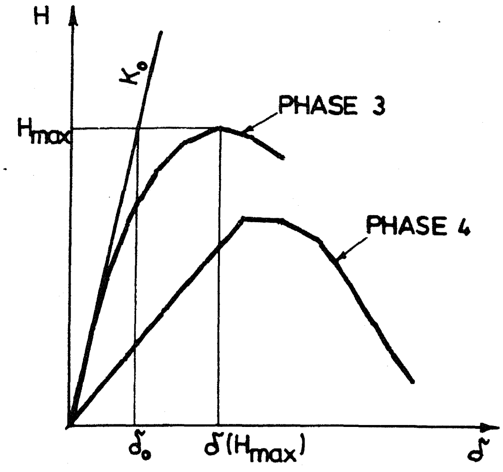

FIG. 3: TYPICAL H - δ̃ DIAGRAM

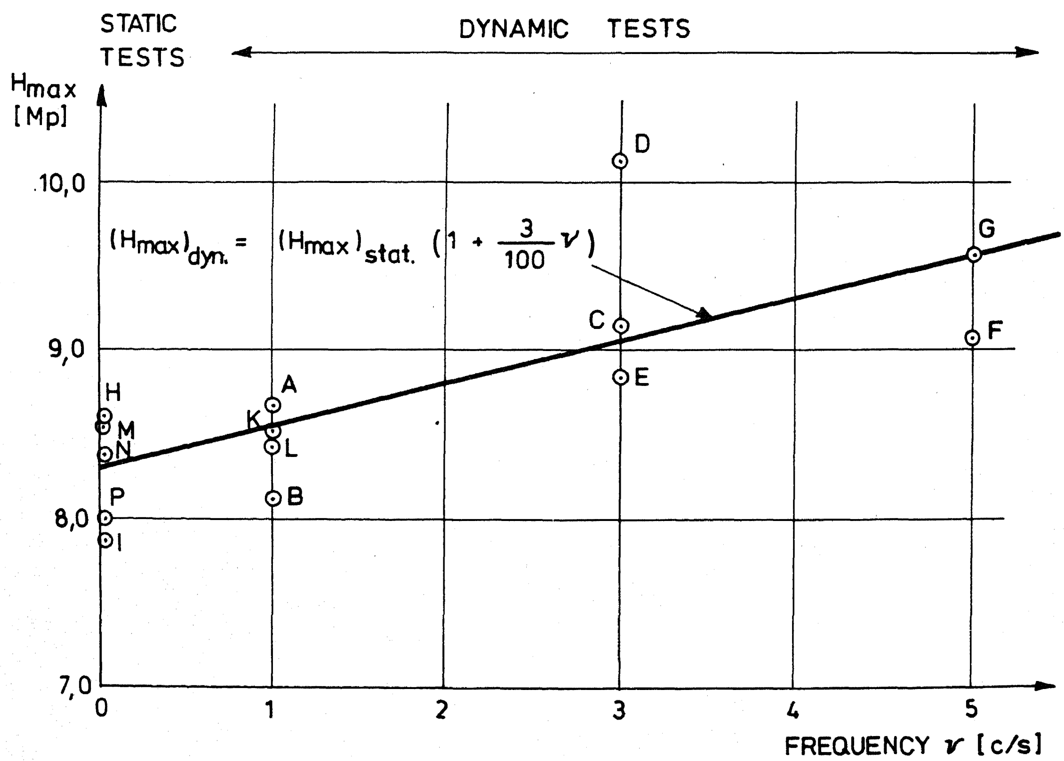

FIG. 4 : H_{max} PLOTTED AGAINST FREQUENCY ν

TABLE 1

	Frequency	Wall	Shear strength H_{max}	Initial stiffness K_o	Displacement $\delta(H_{max})$	Ductility D
	c/s		Mp	Mp/mm	mm	-
"STATIC" TESTS	0,02	H	8.60	2.70	6.8	2.10
		I	7.90	2.25	5.8	1.65
		M	8.60			
		N	8.40			
		P	8.00			
"DYNAMIC" TESTS	1,0	A	8.65	2.25	7.6	1.95
		B	8.15	1.65	7.4	1.50
		K	8.55	2.40	5.8	1.60
		L	8.45	2.25	5.4	1.40
	3.0	C	9.15	2.15	7.2	1.70
		D	10.15	2.45	7.8	1.85
		E	8.85	1.95	7.7	1.70
	5,0	F	9.05	2.55	6.9	1.90
		G	9.55	2.50	7.7	2.00

DISCUSSION

P. Krishnan (India)

Assumption of a linear increase in the shear strength of a wall with frequency does not appear to be justified. The results of the tests described in the paper also do not substantiate this hypothesis. Perhaps an exponential relationship of the type

$$(H_{max})_{dyn} = (H_{max})_{stat} \quad (1 + C\gamma^{1/n})$$

or

$$(H_{max})_{dyn} = (H_{max})_{stat} \quad (1 + C\gamma)^{1/n}$$

Where C and n are constants may be a more fitting equation. More test results would be equired to establish a reliable formula.

The authors have not elaborated how they have arrived at the conclusion that if dynamic tests are to be carried out a single loading frequency of 1.0 c/s can be chosen.

T. Paulay (New Zealand)

Fig. 4 shows that results are not significantly affected by the frequency of loading. Dr. Sheppard suggested that in the future 1 c/s load frequency will be used. Why couldn't a more simple cyclic reversed static loading system be used ?

Author's Closure

With regard to the question of Mr. Krishnan, we wish to state that in principle, any model based on statistical procedures can be used to define the relationship between shear strength and frequency; better models have values of the correlation coefficient "γ" nearer to 1. It was shown by means of the tests that the increase in shear strength with increasing frequency is relatively small. It can therefore be concluded that the shear-strength values obtained from static loading tests may still be made use of, particularly if one considers the scatter of results which is common to all tests of masonry elements. For the shear-strength testing of walls in the laboratory we chose a frequency of 1 c/s since in this case the test is a dynamic one and takes place at a frequency which is near enough to the expected frequency of oscillation during earthquakes, while at the same time measuring techniques are kept relatively simple.

With regard to the question of Mr. Paulay, we wish to state that in any case, whatever kind of test is carried out, static or dynamic, it will be necessary to fix the frequency or rate of deformation and the method of loading (the stepped increases of displacement or load) if comparability between test results is to be achieved. This is particularly so if the complete set of hysteresis loops for the inelastic region all the way to collapse of the wall is to be obtained.