MODEL MATERIALS SUITABLE FOR DYNAMIC TESTS OF MODELS IN THE PLASTIC RANGE

by

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SYNOPSIS

Dynamic model tests in the plastic range can be carried out at ZRMK, Ljubljana with existing equipment. For this to be possible the laws of model similarity must be known and suitable model materials which can fulfill the necessary conditions must be found. Ideally, materials which fulfill the conditions of complete model similarity should be found,and in this direction investigations are going on. In this report some suggestions are given as to how the dynamic characteristics of materials could be determined and as to how reinforcement could be effected with materials which, with respect to their properties, are the same as the reinforcement materials for the prototype.

* * *

The analysis of complicated structures subject to dynamic loads in the plastic range is certainly one field where model experimental techniques have an advantage over computational methods. For the carrying out of such model tests to be possible the laws of model similarity must be known, and special equipment is needed for the application of loads and for the making of measurements. As well as this model materials must be found.

Model techniques have been being developed at ZRMK for a considerable number of years. The Institute possesses various items of equipment for the application of dynamic loads, which are steered according to any chosen program. Included among them are a shaking-table for the testing of models and structural elements, equipment for the testing of full-scale elements under combined (vertical/horizontal) loading, and new equipment for the testing of model elements under combined loading.

The problem, which is partly solved, is in the model materials. If we consider that the choosing of suitable model materials for model tests with static loading is a difficult enough task, then it is clear that the finding of suitable materials for dynamic model tests is so much the harder. In the case of static modelling most researchers follow the rule that the most suitable material is the one which according to its composition and source is similar to the prototype. Such a starting-point for the choice of a model material leads to modelling under conditions of general model similarity or in special cases to simple model similarity. However neither kind of modelling fulfills the condition:

$$\delta = \beta/K_1$$

where δ is the scale factor of similarity for density, β the scale-factor of similarity for stress and K_1 in the scale-factor of similarity for lengths (the modelling scale).

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Because of variance from the above-metioned condition it is necessary to make up for the lack of stress caused in the model by its own weight. In statical modelling compensation is carried out by the adding of weights onto particular parts of the model; some well-equipped laboratories make use of tests in centrifuges and even in linear accelerometers. For dynamic model tests, of the quoted possibilities only the method of adding weights is used, which is not the best solution. It has to be considered, namely, that in this case the mass of the model is increased, the stiffness of its elements is changed, and new centres of gravity are created, bringing with them disturbances in the model. A better alternative involves the loading of the model with weights hanging on long wires. In this way the mass of the model does not change, only its weight is increased. Both the quoted methods are approximate as it is possible to load only a finite (usually small) number of points on the model. As well as this, special space-extensive solutions as to testing equipment are needed for the hanging of the weights. The condition $\delta = \beta/K_1$ is sometimes fulfilled by the regulation of the coefficient of similarity δ, that is to say by the choosing of model materials whose density is K_1 - times greater than the density of the prototype. Model tests of this kind are very much limited by the modelling scale. Clearly it is not possible to increase density indefinitely without at the same time departing from the other conditions for the physical properties of the model material.

At ZRMK it was decided that the path chosen by the Russian expert for model tests, Nazarov should be followed. In this case an attempt is made to fulfill the condition $\delta = \beta/K_1$ with the additional condition $\beta = K_1$, which means that the densities of the prototype and model materials are kept equal, whereas stresses, moduli of elasticity and other physical quantities with the same dimensions are reduced with the scale -factor of lengths. This method of modelling is called complete model similarity (Col.1 in the table). It is understandable that in everyday practice excessive costs prevent the perfect fulfillment of all the conditions of complete model similarity in connection with the physical properties of materials, so use is made of general model similarity (Col. 2 in the table). In this case variations from the set conditions must lie within limits agreed in advance and the condition $\delta = \beta/K_1$ must be fulfilled. The use of complete model similarity is perfectly logical, as all events occur in the modul at a K_1 - times lower state of stress than in the structure, while accelerations and stress gradients remain the same.

Table: Coefficients of similarity for some of the more important parameters of complete and general model similarity

		1 Complete model similarity	2 General model similarity *
K_1	Length	K_1	K_1
K_σ	Stress,Modulus of Elasticity	K_1	$K_1 \cdot \delta$
K_ε	Strain	1	γ
K_Δ	Density	1	δ
K_μ	Poisson's ratio	1	ϕ
K_d	Log.decrement of damping	1	ψ
K_h	Displacement	K_1	$K_1 \cdot \gamma$

K_p	Force	K_1^3	$K_1^3 . \delta$
K_t	Time	$\sqrt{K_1}$	$\sqrt{K_1 . \gamma}$
K_v	Velocity	$\sqrt{K_1}$	$\sqrt{K_1 . \gamma}$
K_w	Acceleration	1	1
K_f	Frequency	$1/\sqrt{K_1}$	$1/\sqrt{K_1 . \gamma}$
K_g	Stress gradient	1	δ

* Column valid if condition: $\delta = \beta/K_1$ is fulfilled.

The conditions which model materials are to fulfill are thus known; the only problem which remains is how to find the materials themselves. At ZRMK extensive tests have been carried out in the field of micro-concrete, and most recently very considerable advances have been made in the modelling of masonry buildings for dynamic tests. Experience gained so far has shown that it is possible to find suitable materials for the modelling of concrete, of materials for the making of building-blocks, mortars and of other similar prototype materials which satisfy the majority of the conditions for physical properties. The only question is, to what extent do these materials fulfill the conditions connected with dynamic characteristics, for example the condition which requires equality of logarithmic decrements of damping. It will therefore be necessary to select from the list of model materials for static modelling under conditions of complete model similarity those materials which fulfill all the conditions for dynamic tests. Such a selection can be carried out by means of tests of suitable prototype and model test-samples, where the latter are excited with impulses and the free damped motion is recorded, or else where they are subjected to cyclic combined (vertical/horizontal) loading and the shapes of hysteresis loops are determined. On the basis of comparisons between values obtained in the case of prototype or model test-pieces for the logarithmic decrement of damping or for the surface-area and shape of the hysteresis loops, model materials which fulfill the conditions for dynamic tests are chosen. Experience has shown us that for comparisons it is more useful to use building elements (e.g.beams, walls,columns etc.) instead of the simplest kinds of test-samples which are otherwise used for the determination of material properties.

As there exists at ZRMK a well-established method for the determination of the dynamic characteristics of building elements which uses equipment for testing under dynamic combined loading (dynamic horizontal cyclic-loading with simultaneous vertical loading), it was decided that an attempt should be made to master an analogous method for the field of model tests. Recently equipment was built for the dynamic combined loading of model elements, which can be connected onto the program for the prototype, reduced in the direction of displacements by the scale-factor K_1 and in the direction of frequency by the scale-factor $1/\sqrt{K_1}$. A direct comparison of the hysteresis loops obtained on prototype and model elements makes possible good selection between model materials. To what extent there can be variation from the conditions for the dynamic characteristics of models has to analysed separately for each case. Certainly the variations have to be as small as possible in cases where the model is loaded by means of forced vibrations applied to its base, i.e. in the case of model tests on the shaking-table. The mass and the dynamic characteristics of model materials have direct influence on the dynamic behaviour of the model as a whole.

Although a wide range of basic materials for the making of model materials exist for the modelling of concrete, buildingblocks and mortars etc., possibilities are considerably limited in the modelling of reinforcement. If one takes for example ordinary steel for concrete reinforcement then one can see that see that the $\sigma - \varepsilon$ diagram is quite specific and that among other materials it is not possible to find such as would have equal deformability properties (γ=1) and K_1-times reduced strength properties (see Fig.1). From the literature it can be seen, in cases where, when modelling, states of stress with lower stresses are reached, that reinforcement bars made of some of the non-ferrous metals or even of various plastics are used. These materials, according to the shape of their $\sigma - \varepsilon$ diagrams, do not approach the required shape closely enough. Thus it is only possible to use them in the elastic range or else in a limited lower part of the plastic range.

At ZRMK a decision was made in favour of the modelling method where simply the prototype-material is retained for the reinforcement of models, cross-sectional areas being so reduced that an equivalent result is finally obtained. From the table it is clear that the model reinforcement must take on a $K_1{}^3$-times smaller force, while strains in the prototype and in the model must remain the same. If when modelling reinforcement the physical properties of the reinforcement of the prototype are retained, then a correct acceptance of forces is obtained only when the cross-sectional area of the reinforcement is reduced by the coefficient $K_1{}^3$. Apart from the normal reduction of reinforcement diameter with the coefficient K_1 it is necessary in the case of the quoted method of modelling to reduce the reinforcement diameter additionally by the coefficient $\sqrt{K_1}$, which gives the total required reduction in cross-sectional area of $K_1{}^3$. The consequences of such a reduction are that the circumference of the reinforcement is reduced by $\sqrt{K_1}$-times too much with respect to the circumference which the reinforcement in the model should have in accordance with the conditions of model similarity. It follows from this that a similar occurrence of cracks in the model cannot be expected, as the variation mentioned results in too little adherence between the reinforcement and the surrounding material. In the case of structures where the width and distance of separation of cracks are not essential for the development of the observed phenomena, the fact that the circumference is incorrectly modelled can be neglected. In cases where the cracks themselves are of essential importance it is necessary to get rid of this incorrectness. The way out of these difficulties lies in the artificial roughening of the surface of the model reinforcement. The roughening can be most easily carried out, in our opinion, by the spraying-on of a layer of rough plastic, which only increases the friction between the reinforcement and the model concrete, but does not alter the strength and deformability characteristics of the reinforcement. Such a method of correction must of course be checked with pull-out tests.

The $\sigma - \varepsilon$ and P-ε diagrams now have the shapes shown in Fig.2. Here it should be noted that the P-ε diagrams in Figs.1 and 2 are, in spite of the difference between the $\sigma - \varepsilon$ diagrams, equal, a fact which is essential for the modelling case being dealt with. The principle of the described method of modelling can be seen clearly in the diagrammatic view of the state of stress in the reinforced-concrete beam shown in Fig.3.

The object of this paper has been to point out some of the important problems which arise in the choosing of materials for dynamic model tests in the plastic range and the ways in which these problems are being solved at ZRMK. We shall consider the task completed only when we have available a sufficient number of model materials for the making of models of any chosen structure which will fulfill the conditions of model similarity not only for static tests but for dynamic tests as well. A wide range of such model materials can only be made possible if there is organized cooperation between those laboratories which are interested in the development of model techniques.

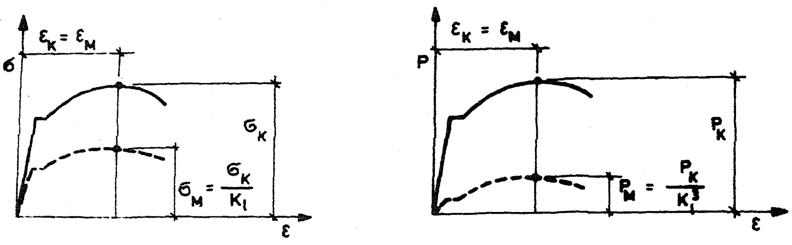

FIG. 1

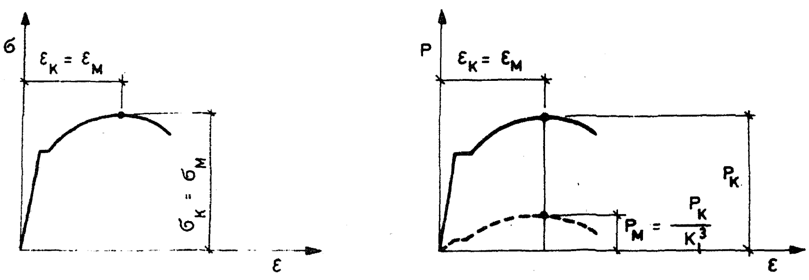

FIG. 2

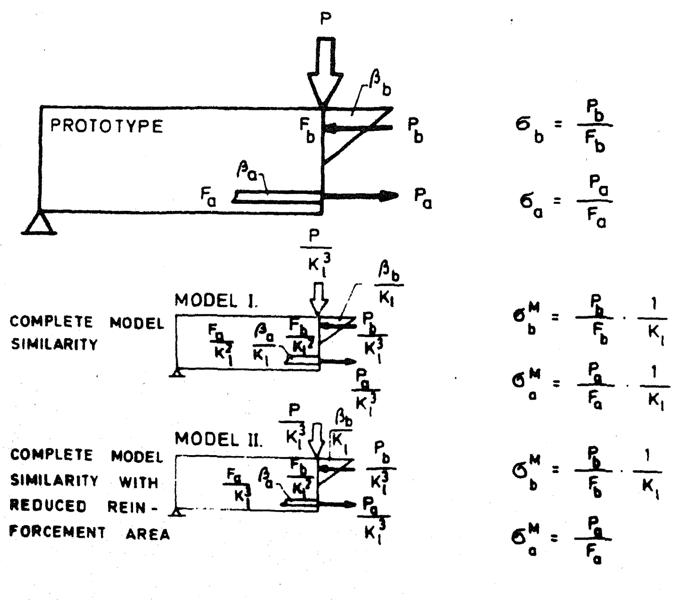

FIG. 3

DISCUSSION

B.R. Seth (India)

The authors have suggested spraying the reinforcement in model by rough plastic to overcome the extra reduction in circumference, in my opinion the layer of plastic shall not transfer the strains from surrounding material to steel faithfully and alter the behaviour completely.

H. Kranwinkler (U.S.A.)

From your presentation it appeared that you have used prototype material for your model tests. This will not lead to proper simultaneous simulation of gravity and inertia forces since the density of the model material should be inversely proportional to the length scale. How did you correct for this problem.

Author's Closure

With regard to the question of Mr. Seth, we wish to state that in the paper the author proposed the use of prototype materials for the reinforcing of models which are modelled in accordance with the conditions of complete model similarity. In this case it is necessary to carry out, apart from the reduction in cross-sectional area due to the modelling-scale, an additional correction of the cross-sectional area. This additional correction brings about a reduction in the circumference of the model reinforcement and, as a result of this, a reduction in the bond between the reinforcement and the concrete. In the paper the author quoted the idea, that suitable roughening of the model reinforcement could be achieved by the spraying-on of a layer of plastic. This roughening would result in the same ocurence of cracks as in the case of a cross-sectional area without the additional reduction. The sprayed-on layer should be thin and its surface suitably roughened. In order to provide practical confirmation of this idea a program of tests has been drawn up. These tests are based on a comparison of pullout and bending tests, carried out on prototypes and models. The tests are still in the process of being carried out at the present time. The author should be reporting on the results at a later date.

With regard to the question of Mr. Kranwinkler, we wish to state that if model materials, which according to their mechanical characteristics behave like the prototype materials (simple model similarity), are used for the construction of models, then difficulties do occur in connection with the making-up for lack of own weight. These difficulties are particularly great when modelling for dynamic model tests.

The essence of my paper has been that in it I have proposed that modelling be carried out under conditions of complete model similarity, the latter being a much more suitable method of modelling. For in this case the above-described difficulties can be avoided through a suitable correction of 1) the mechanical characteristics of the model materials and 2) the loads on the model.