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Marianna GLENSZCZYK *

EXPERIMENTAL - COMPUTATIONAL METHOD OF REINFORCED CONCRETE CONSTRUCTIONS TESTING

1. Introduction

The basis of any considerations regarding reinforced concrete constructions is an experiment. Experiments are necessary at both stages: discovering the way the elements or structures work and adapting theoretical methods to their practical usage.

In view of thousands of available worldwide results of reinforced concrete elements tests it seems, that the simplest way would be to use existing results. However, because of the unique character of these tests, it is not always possible to use the results (in experimental sense) for different elements, and we are constantly forced to conduct new experiments. This leads to large financial and time efforts and is connected with a lot of problems, especially in case of statically indeterminate reinforced concrete elements.

Thus, according to current tendencies [1], new methods for experimental testing are being developed. Among other things, work leading to an improvement of theoretical moment-curvature relationship is following that trend. It is important to artificially create conditions similar to the ones, in which actual tests have been conducted, by introducing dimentional and material inaccuracy [2, 3] and loads [4] as random variables.

Efforts are being made at Gliwice Research Centre ** to increase the number of experimental tests, and they follow a different direction.

They consist on connection of the results, obtained from tests on small fragments of the construction, with a suitable calculating method.

* Doctor Eng. Silesian Technical University, ul. Pstrowskiego 5
44-100 Gliwice, Poland

** Institute of Building Structures

Tests refer to one-way reinforced isostatic slabs [5, 6], hyperstatic slabs [5, 7] and to precast wall structures [8, 9]. In this paper the essence of proposed way of testing reinforced concrete element and structures* is presented, together with chosen examples of its practical usage.

2. The essence of the method

2.1. General description

The way of increasing the number of experimental tests described below, is based on independent testing of adequately chosen parts of an element or structure and subsequently integrating them mathematically, using a computer. The basis of this method is the knowledge of deformation characteristics of element or structure parts, selected in such a way, that all the material, geometrical and resistance-deformation characteristics remain unchanged within each part. Parts defined as above can be combined together in different configurations, therefore it is possible to test the entire family of elemnts different span, reinforcement varying on the length, free combination of the loads or structures different types of joints, varying reinforcement and floor slab span .

For example, a floor slab, which is a fragment of a wall structure fig. 1 , consists of three parts, differing in the amount of reinforcement a different percentage of tensile reinforcement in the supports and in the span . Each one of these parts has a different deformation characteristic, comprising the entire range of loads.

In case of a slab shown on fig. 1, certain deformation characteristics are described by non-linear moment-curvature relationship.

Also the joints 1 and 2 regardless of the obvious fact, that one is an external and the other an internal joint can be constructed entirely differently. This is fully reflected by joint deformation characteristic , describing the non-linear relation between the fixing

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* In previous publications this way is called the experimental-computational method of structure testing

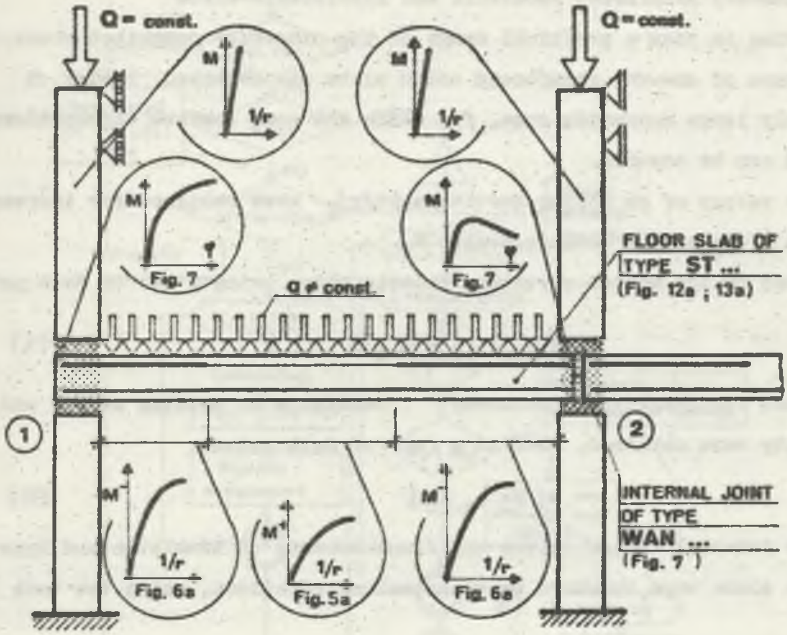

Fig. 1. Fragment of a wall structure - assumptions of presented method

moment and mutual angle of rotation of joined floor and wall slabs (fig. 1).

In the example discussed here, a linear moment-curvanture relationship was accepted for wall structures, relating to assumed level of vertical loads.

In the presented method of construction testing, combining of individual fragments of given element or structure is performed mathematically. As the procedure discussed here is equivalent to direct testing, it is valid only for precisely described types of constructions. It refers only to those element, for which it possible to obtain, by testing, the mean acting curvature, reliable for any, freely chosen level of loads.

All kinds of wall structures and slabs (reinforced concrete and prestressed slabs, solid and hollow-core slabs) fulfil above conditions.

2.2. One-way reinforced isostatic and hyperstatic slabs

Having in view a practical usage of the procedure described above, the curvature of one-way reinforced solid slabs was obtained, basing on suitably large measuring area, for which the mean surface deformations [5, 6] can be assumed.

The values of an acting curvature $(1/r)_i$ were assigned for increasing values of an acting bending moment M_i.

Based on the moment-curvature relationship, being a set of data pairs

$$\{ M_i \, ; \, (1/r)_i \} \tag{1}$$

assigned for spacific structures *, relations of bending moment and rigidity were obtained, also in a form of data pairs

$$\{ M_i \, ; \, B_i \} \tag{2}$$

The internal forces values and displacements of isostatic and hyperstatic slabs were obtained by numerical calculations, using the data set (2).

The necessary condition, while moving from the tested slabs to freely loaded isostatic or hyperstatic slabs, was to assumpt, that identical deformation characteristics exist between them.

Practically, the above assumption means, that any analysed slab consists of parts, each having the identical deformation characteristics, as tested slabs of a given type (see table 1). In consequence, on each fragment of the calculated slab, certain relations, obtained experimentally, are assumed.

Continuous slabs were calculated, using the iterative method, by suitably adopted PROBUS system. A new procedure, called MOSUS - fig.2b, was added, and it containes:

- modification of structure rigidity,
- changes of loads,
- modification of statical schemes (see fig.2a).

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* This describes a set of material, geometrical and resistance features (eg. a slab with a given cross-section, type and percentage of reinforcement, with set up resistance parameters).

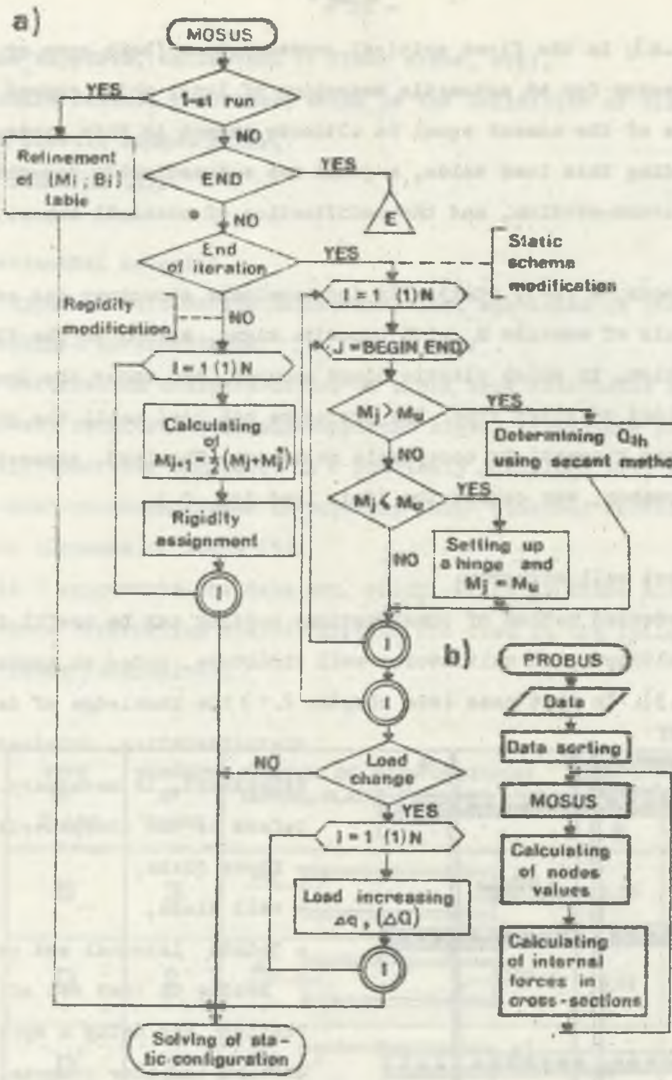


Fig.2. Flow-chart of MOSUS procedure and its localisation in PROBUS system

The structure rigidity modification was performed for each i-level of load, and the movement to an (i+1)-level was done automatically (after achieving the compatibility between bending moment and its bending rigidity) at previously given increment of load (ΔQ or Δq). The attainment of the value greater than the ultimate moment value M_u

(see fig4-6), in the first critical cross-section (both span or support), was the reason for an automatic searching of load, which caused the appearance of the moment equal to ultimate moment in this cross-section. After finding this load value, a joint was automatically brought into the critical cross-section, and the modification of statical scheme had taken place.

Afterwards, a (n-1) statically indeterminate structure was calculated, under a pair of moments M_u with opposite signs, acting in the first cross-section, in which plastic hinge occured, and under the increasing external load of given type. The procedure was used until the structure changed into kinematicly acceptable mechanism. The load, connected with this phenomenon, was called the limit load (q_L, Q_L).

2.3. Precast wall structure

The presented method of constructions testing can be useful for analysing of multispan and multistorey wall structure, under an instantaneous load (fig.3). In that case (see chapter 2.1) the knowledge of deformation characteristics, obtained by an experiment, is necessary. Above refers to the characteristics of:

- floor slabs,
- wall slabs,
- joints internal and external .

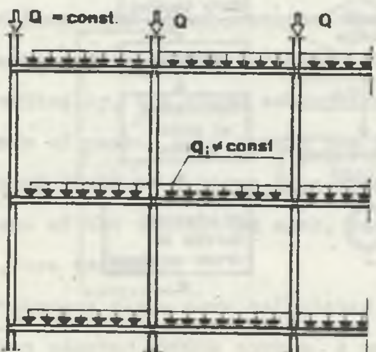


Fig.3. An analysed wall structure

Basing on that set of characteristics, and using a specially created computer program, a set of computational curves (see chapter 4.2) was obtained, enabling to observe the structure work in an entire range of loads: starting with elastic state, through cracking state and up to plastic hinges apperance state.

Because of previously determined range of this paper, more details are not described. The detailed description of:

- structure behaviour under increasing values of load q_i (fixing moment at the supports, deflection of floor slabs, etc),

- structure failure character, which is the definition of order, in which plastic hinges occur,

can be found in [9].

3. Experimental material

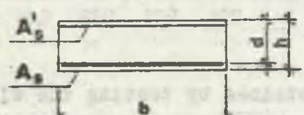
All types of deformation characteristics, mentioned in chapter 2.1, were obtained by experiment.

The deformation characteristics of slabs were determined by examining the one-way reinforced, simply-supported slabs, under pure bending. The investigations were conducted in a precisely described way, enabling one to get mean curvature (mean of suitably large measured surface), varying with the increase of loads [5].

Table 1 represents the data set, which refers to those slabs (structures), whose deformation characteristics are used in the following part of the paper (chapter 4).

TABLE 1

TYPE OF SLABS	NUMBER OF SLABS	POSITION OF REINFORCEMENT DURING SLABS' FORMING	PERCENTAGE OF REINFORCEMENT ϱ	PERCENTAGE OF REINFORCEMENT ϱ'
B	3	A'_s A_s	0,36	0,19
D	2	A'_s A_s	0,42	0,19
D'	2	A_s A'_s	0,19	0,42
E	2	A_s A'_s	0,81	0,42
E'	2	A'_s A_s	0,42	0,81



$\varrho = \frac{A_s}{bd}$; $\varrho' = \frac{A'_s}{bd}$;

TESTING SCHEME

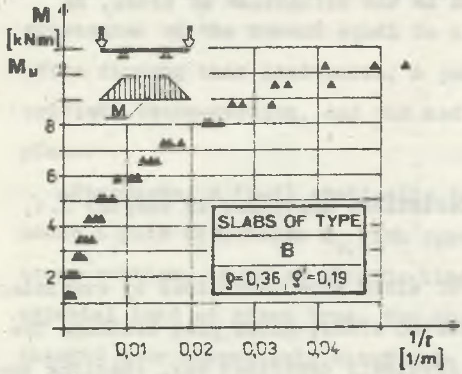


Fig.4. Moment-curvature relationship obtained by testing the slabs of type B (reinforced with a ribbed steel)

Fig.4 shows an experimental moment-curvature relationship, obtained for slabs reinforced with a ribbed steel, and fig.5 and 6 show the same relationship, obtained for slabs reinforced with a smooth steel.

The deformation characteristic of joint was developed from tests, realised on parts of horizontal joints, with a constant value of vertical loads acting on the walls. The results of mutual rotational angle of wall slabs and floor

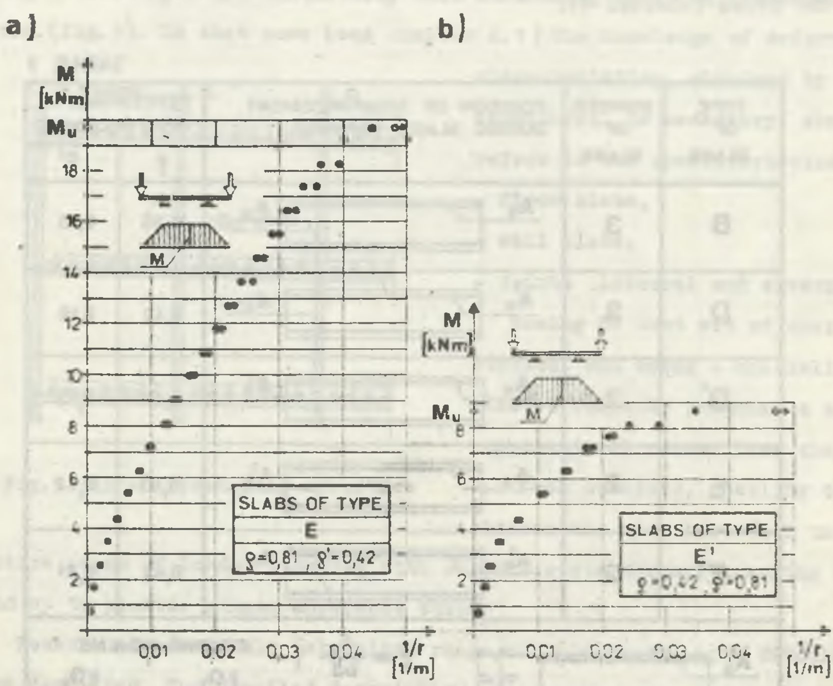


Fig.5. Moment-curvature relationship obtained by testing the slabs a) of type E, b) of type E' (reinforced with a smooth steel)

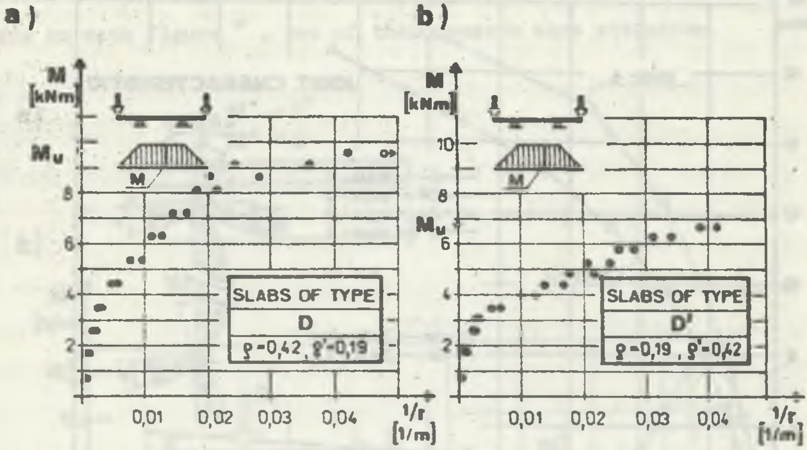


Fig.6. Moment-curvature relationship obtained by testing the slabs a) of type D , b) of type D´ (reinforced with a smooth steel)

slabs were taken, while the loads of floor slab fragments were increasing gradually.

The above testings represent the development of the idea of investigations of slabs joints, conducted at the Centre for Building Systems Research and Development in Warsaw, and directed by B.Lewicki [10].

Two different types of horizontal joints were tested: the first one was a simply-supported floor slab, while the second one was a continuous joint of slabs.

Fig.7 shows four characteristics of internal joint and two characteristics of external joint, obtained from available experimental material.

The proposed method of construction testing was veryfied by comparing measured and calculated deflection values. The veryfication was performed for simply-supported solid slabs, reinforced both with smooth and ribbed steel[5,6],and also for hollow-core slabs, prestressed by using thermal method (electroheat). A mean relative error (calculated for a whole range of loads) was ≈ 4.5% in case of reinforced slabs (in a range from 1 to 10%), and ≈ 8 % for prestressed slabs.

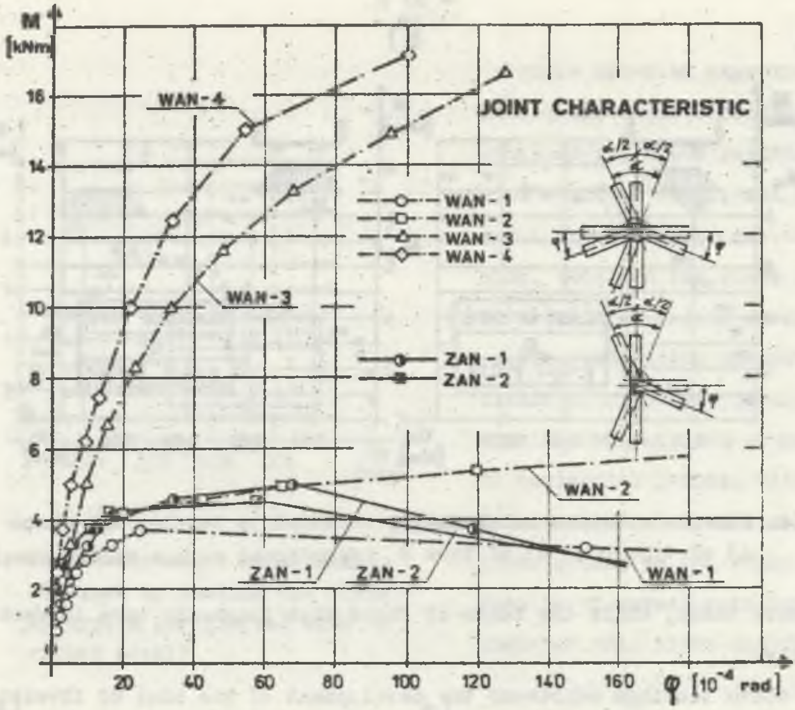


Fig. 7. Deformation characteristics obtained by testing the internal joints (WAN-1 - WAN-4) and external joints (ZAN-1 - ZAN-2)

4. Chosen examples of using the experimental-computational method of structure testing

4.1. Hyperstatic slabs

The way of slabs testing, presented in chapter 2, was used to analyse the behaviour of three-span slabs (fig. 10) and slabs fixed at both ends (fig. 8, 9, 11). The slabs consisted of parts, each having the identical deformation characteristics as the ones, obtained by testing (for slabs listed in table 1).

One of the most important factors, which have a decisive influence on moments redistribution value in reinforced concrete structures, is "compatibility" of the reinforcement. A known fact is, that any departure from the amount of reinforcement, calculated on basis of linear structure analysis [11], leads to rearrangement of bending moments (moment redistribution). Despite the fact, that the influence of that factor appears on each figure *, two of them deserve more attention.

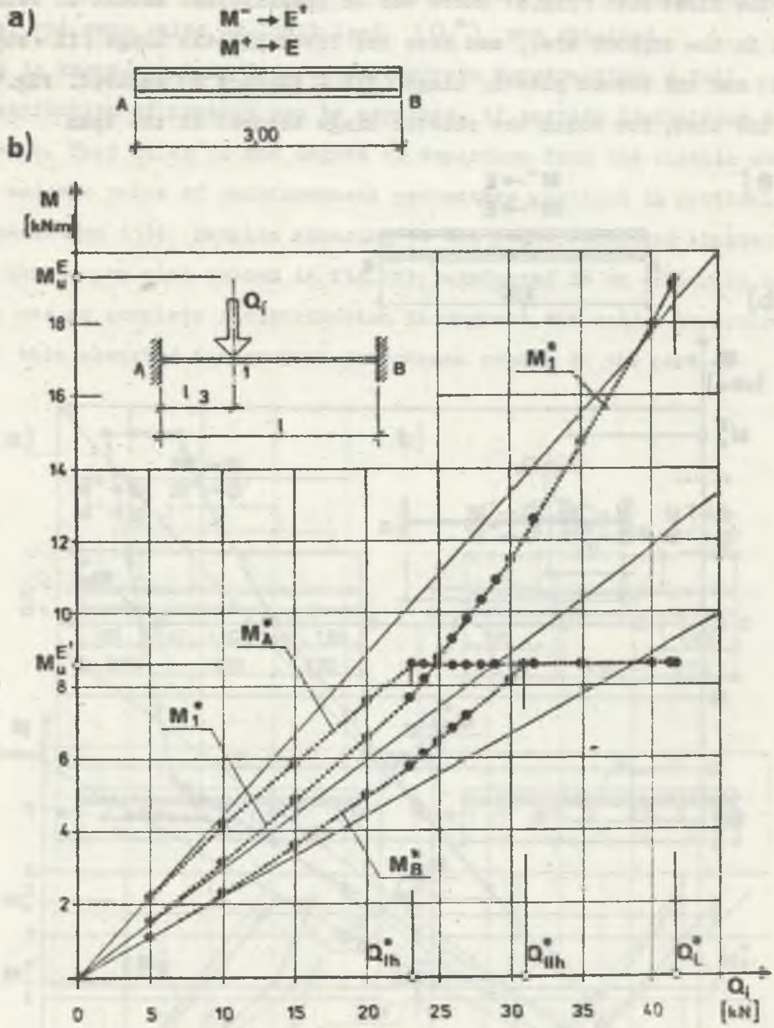


Fig.8. A slab fixed at both ends - insufficient amount of reinforcement in the support cross-sections a) slab reinforcement, b) moments redistribution

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* Marks on fig. 8÷11: points - the values of bending moments numerically calculated, broken line - probable path of moments between points, full line - the values obtained from linear structure analysis.

Fig.8 and 9 show the slabs with an equal, total amount of reinforcement on supports and span /0,5 (ϱ_A + ϱ_B) + ϱ_1 = const/.

In the first slab (fig.8) there was an insufficient amount of reinforcement in the support area, and here the first plastic hinge (Ih – support A) and the second plastic hinge (IIh – support B) occured. Fig.9 shows the slab, for which the plastic hinge occured at the span

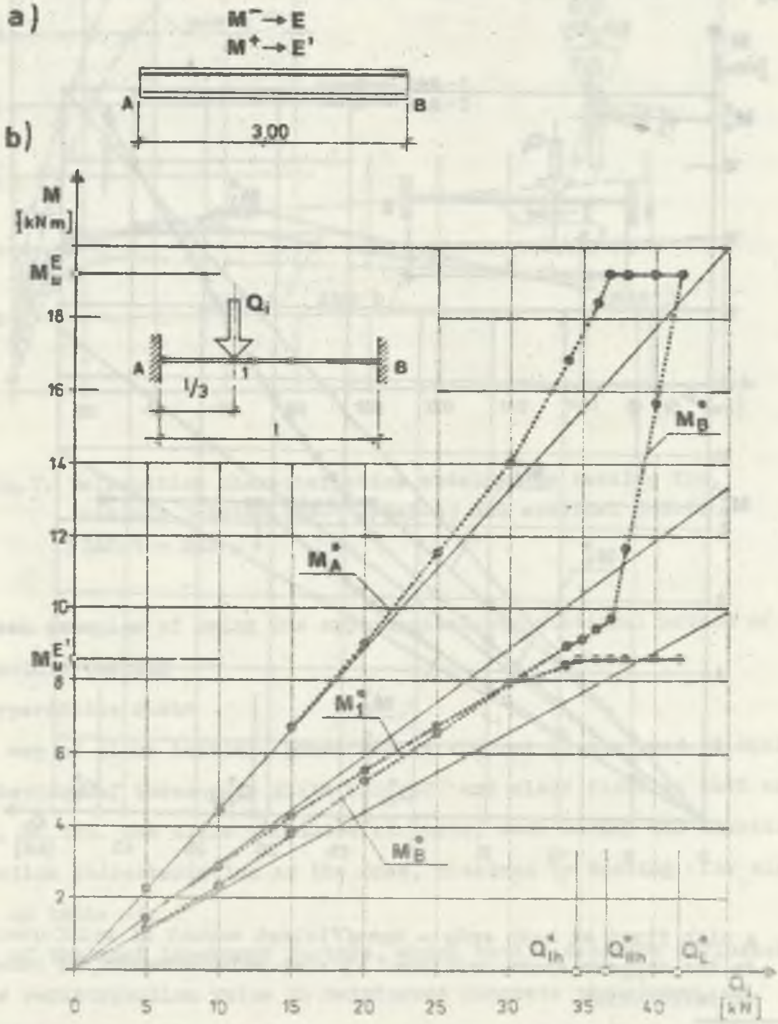

Fig.9. A slab fixed at both ends – insufficient amount of reinforcement in the span cross-section a) slab reinforcement, b) moments redistribution

cross-section first, and then subsequently at both support cross-sections.

According to theoretical considerations, for both slabs described above, the same value of limit load (Q_L^*) was obtained.

It is known, that in reinforced concrete constructions a full redistribution of moments can be expected, if certain limitations are observed. They refer to the degree of departure from the elastic state [12] and the value of reinforcement percentage quotient in critical cross-section [13]. Despite adhering to the above mentioned limitations, in a three-span slab (shown in fig. 10), reinforced in an arbitrary way, there was no complete redistribution throughout the entire structure. It seems this observed destruction phenomenon occurs in the part of

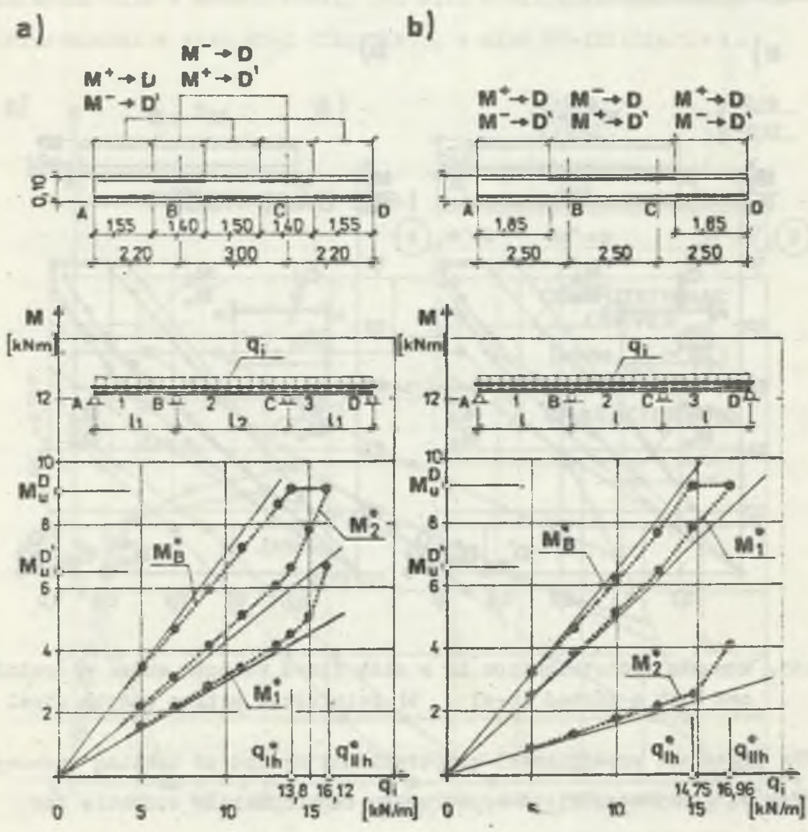

Fig. 10. Moments redistribution in three-span slabs; a) middle span failure, b) extreme spans failure

a structure before reaching load capacity in all cross-sections, and is the most frequent cause of destruction of the continuous reinforced concrete structures, with more than two spans. There is always a complete redistribution in two-span structures (according to existing studies).

Fig.11 shows the effect of the type of reinforcing steel on moments redistribution. The reinforcement was selected in a way to receive the same value of reinforcement percentage quotient in critical cross--sections. The type of changes of the bending moments in slabs, reinforced both with ribbed (fig.11a) and smooth (fig.11b) steel in the entire range of loads, appeared to be very similar. Ribbed steel proved to be fully suitable in view of the possibility of the redistribution phenomenon appearance.

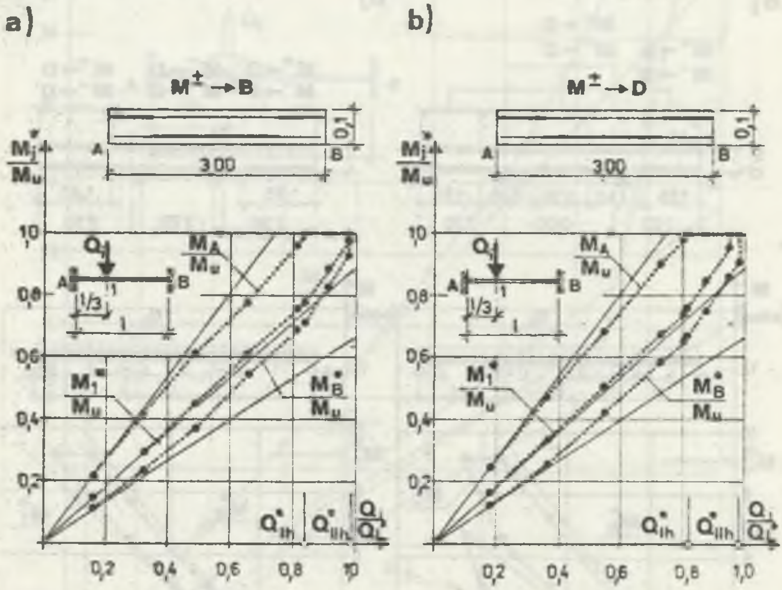

Fig.11. Moments redistribution in a slab fixed at both ends: a) reinforced with a ribbed steel , b) reinforced with a smooth steel

The presented experimental-computational method of testing one-way reinforced continuous slabs appeared to be completely suitable for analysing their behaviour, in the range of instantaneous loads, increasing to the point of destructure. It is considered, that this method can be accepted as equivalent to testing of presented above slabs.

4.2. Precast wall structure

The experimental-computational method for modelling the behaviour of precast wall structure, was used to present the influence of different deformation characteristics of horizontal joint on the structure work, under instantaneous load. The analysis of an external span of the structure, while having (fig.1):

- the non-linear deformation characteristic for each slab cross-section,
- the non-linear deformation characteristic of the joint is shown below.

Four deformation characteristics of an internal joint and two deformation characteristics of an external joint (fig.7) were used for further considerations. Two types of floor slabs were analysed, both reinforced with a smooth steel, but with a different percentage of reinforcement: a slab ST-I (fig.12a) , a slab ST-III(fig.13a) .

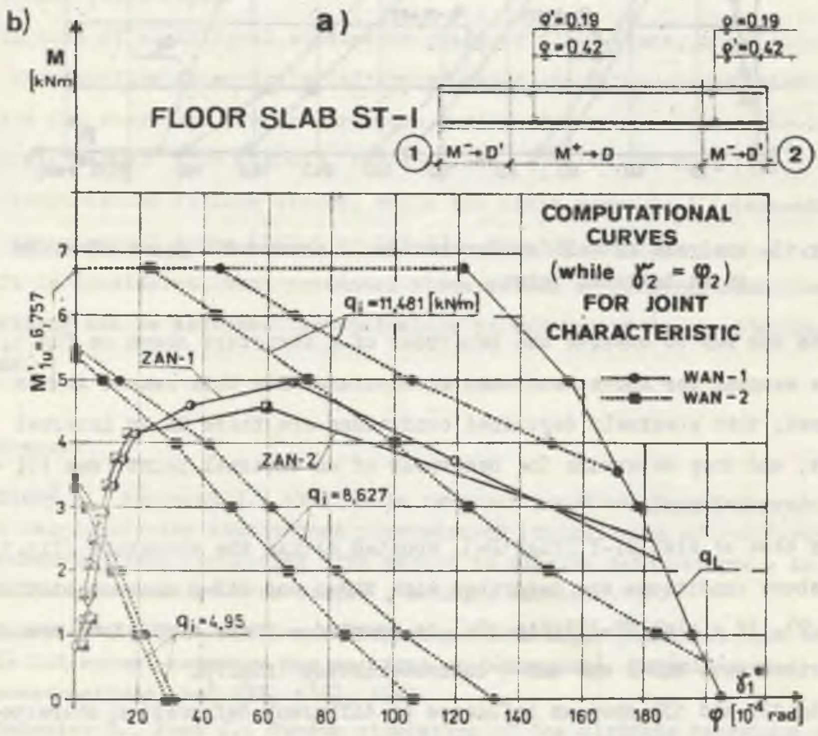

Fig. 12. Analysis of wall structure work - simply supported floor slabs in an internal joint

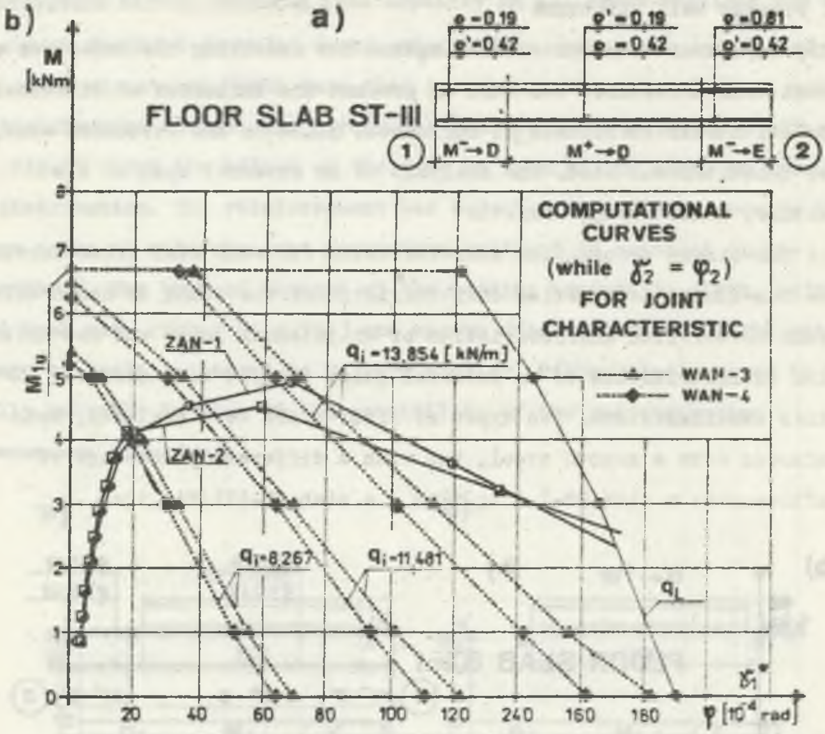

Fig. 13. Analysis of wall structure work - continuous joint of slabs in an internal joint

The aim was to observe the behaviour of a structure shown on fig. 1, while keeping the above mentioned assumptions. For this reason it was assumed, that precisely described conditions are there in an internal joint, and they determine the behaviour of an external joint (see [9] - an external joint).

In case of slab ST-I (fig. 12a), mounted within the structure (fig. 1), the above conditions are described with WAN-1 and WAN-2 characteristics (fig. 7). If a slab ST-III (fig. 13a) is mounted - these conditions are described with WAN-3 and WAN-4 characteristics (fig. 7).

Fig. 12b and 13b show an influence of different deformation characteristics on the structure behaviour.

Computational curves (see [9]), calculated for three values of load q_i (4.95 , 8.627 , 11.481 kN/m) are drawn with a dotted line. Each of these curves represents a set of values: fixing moment - angle of rotation, which can occur in an external joint, for precisely described conditions in an internal joint.

According to the condition of deformational compatibility (at the supports), problem solution sought is the intersection point of the given experimental curve (ZAN-1 or ZAN-2) with the computational curve.

For given type of a floor slab, the paths and character of computational curves for an external joint, change together with the change of conditions in an internal joint.

For example: for the conditions existing in the external joint, described by ZAN-1 characteristic, the load on the floor slabs can reach the value of q_i = 11,481 kN/m only in case, when conditions described with WAN-2 curve occur in the internal joint. The above value cannot be reached if the conditions described with WAN-1 curve exist in the internal joint (fig.13b).

In case of an internal continuous joint of floor slabs, the work of the construction is entirely different (WAN-3 and WAN-4 characteristics): we are far away from the construction failure for the same characteristic of the external joint (ZAN-1), and the load q_i = 11,481 kN/m (fig.13b). The construction failure occurs, while the limit curve (q_L) intersects the experimental curve (ZAN-1 or ZAN-2) - fig.12b and 13b.

It is considered, that presented above method of constructions work modelling can be accepted as equivalent to testing of analysed constructions.

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Summary

The presented method of constructions testing is based on simple tests of adequately selected fragments of an element or structure, and subsequently integrating them mathematically. The connection of independent testing with a suitable computational method (using a computer) enables one to test the entire family of elements (different span, reinforcement varying on the length, free combination of loads) or structures. The application of the method is shown in various examples (chapter 4).

Key words: reinforced concrete structures, wall and floor slabs, internal and external joints, experimental and computational method, deflection, plastic hinge, moment-curvature relationship, deformation characteristic, limit loads, state of failure

DOŚWIADCZALNO-OBLICZENIOWA METODA BADANIA KONSTRUKCJI ŻELBETOWYCH

Streszczenie

W pracy przedstawiono pewien sposób zwielokrotnienia badań doświadczalnych, polegający na niezależnym badaniu odpowiednio dobranych fragmentów elementu lub ustroju, a następnie ich scaleniu metodą rachunkową.

Połączenie wyników niezależnych badań z odpowiednią metodą obliczeń (przy użyciu komputera) umożliwia zbadanie całej rodziny elementów (różne rozpiętości, zmienne na długości zbrojenie, dowolna kombinacja obciążeń doraźnych) lub ustrojów.

Praktyczne wykorzystanie proponowanej metody badania konstrukcji zilustrowano licznymi przykładami dotyczącymi płyt ciągłych oraz ustrojów ścianowych.

ЭКСПЕРИМЕНТАЛЬНО-РАСЧЕТНЫЙ МЕТОД ИСПЫТАНИЯ ЖЕЛЕЗОБЕТОННОЙ КОНСТРУКЦИИ

Резюме

В работе представлен метод повторяющихся экспериментальных испытаний, который состоит в независимом испытании соответствующим образом подобранных фрагментов элементов или систем, а затем их объединение расчетным методом.

Объединение результатов независимых исследований с соответствующим расчетным методом (с использованием компьютера) позволяет исследовать целый ряд елементов (различный размах, переменная по длине арматура, произвольная комбинация временных нагрузок) или систем.

Практическое использование предлагаемого метода исследования железобетонной конструкции проиллюстрировано многочисленными примерами для неразрезных плит и стенных систем.