CEB
27 th PLENARY SESSION
PARIS SEPTEMBER 1990

COMITÉ EURO-INTERNATIONAL DU BÉTON
CONTRIBUTION OF THE POLISH NATIONAL GROUP

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MULTI-STOREY STRUCTURAL SYSTEM CONSISTING OF PREFABRICATED THIN-WALLED ELEMENTS AND CAST-IN-SITU CONCRETE

1. Introduction

In many types of buildings the large spans of skeleton structures in both directions are required from functional and/or architectural reasons. Additionally, in some cases the relatively high storeys and big live loads are required too. These three independent requirements cause some serious structural problems in design and erection of buildings.

The structural system described below was designed mainly according to the demands of modern department stores [1]. The elements of the structure were tested in laboratories, introduced in practice and modified during the period of almost 15 years. Over ten large buildings were erected with partial use of the system elements.

2. General Description of the System

The basic assumptions taken into account at the design were as follows:

- the grid of columns from 9m x 9m to 9m x 12m,
- the height of storeys from 4.5m to 6.0m,
- the live loads from 5.0 to 7.5 kN per square metre, with possible increment to 15 kN/m^2 for the grid of 9m x 9m in heavy loaded stores.

The fire protection requirements were 2 hours for columns and girders, and 1 hour for secondary beams and slabs. In addition, lack of bracing walls for 3-storey to 5-storey buildings has been also assumed.

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Special considerations were devoted to technological problems of the system. To avoid the heavy scaffoldings and shuttering precast members were chosen. However, precast girders and columns of a full, solid section were too heavy to assembly, because the distance at least 30m had to be considered at assembling. Therefore, to connect the benefits of precast and monolithic structures the composite system was designed. The general idea was to combine the thin-walled prefabricated elements, either reinforced concrete or prestressed concrete, with the cast-in--place supplementary concrete.

The prefabricated elements should be made from high-strength concrete with precision to warrant the suitable and accurate assembling works. These elements should be equipped in all the connecting details necessary at assembly and finishing work. The surface of the prefabricates ought to be smooth enough to avoid the plastering and any other finishing works apart from painting.

The prefabricates to be filled with fresh concrete must be provided with the reinforcement carrying all the assembly loads and the average working loads. Since the loads may change in particular parts of building the load-capacity of members under especially heavy loads should be provided with additional reinforcement, but the shape of prefabricates remains constant in their main groups to avoid many types of costly forms.

The supplementary part of sections should make possible placing additional reinforcement, and the cast-in-situ conrete could be of a moderate quality (e.g. C16); in practice ready-mixed concrete placed by pumps or conveyors should be used.

The main idea of the system described is presented in Fig.1, where the arrangement of precast members over the interior and exterior column is presented. The final cross-sections of girders and columns are showed in Fig.2; the share of cast-in-place concrete in these members is relatively big.

3. System Elements

The most numerous members in the structure are the T-beams which create the basic floor surface. The T-beams were designed as reinforced concrete or prestressed concrete elements (Fig.3 a,b,c,d).

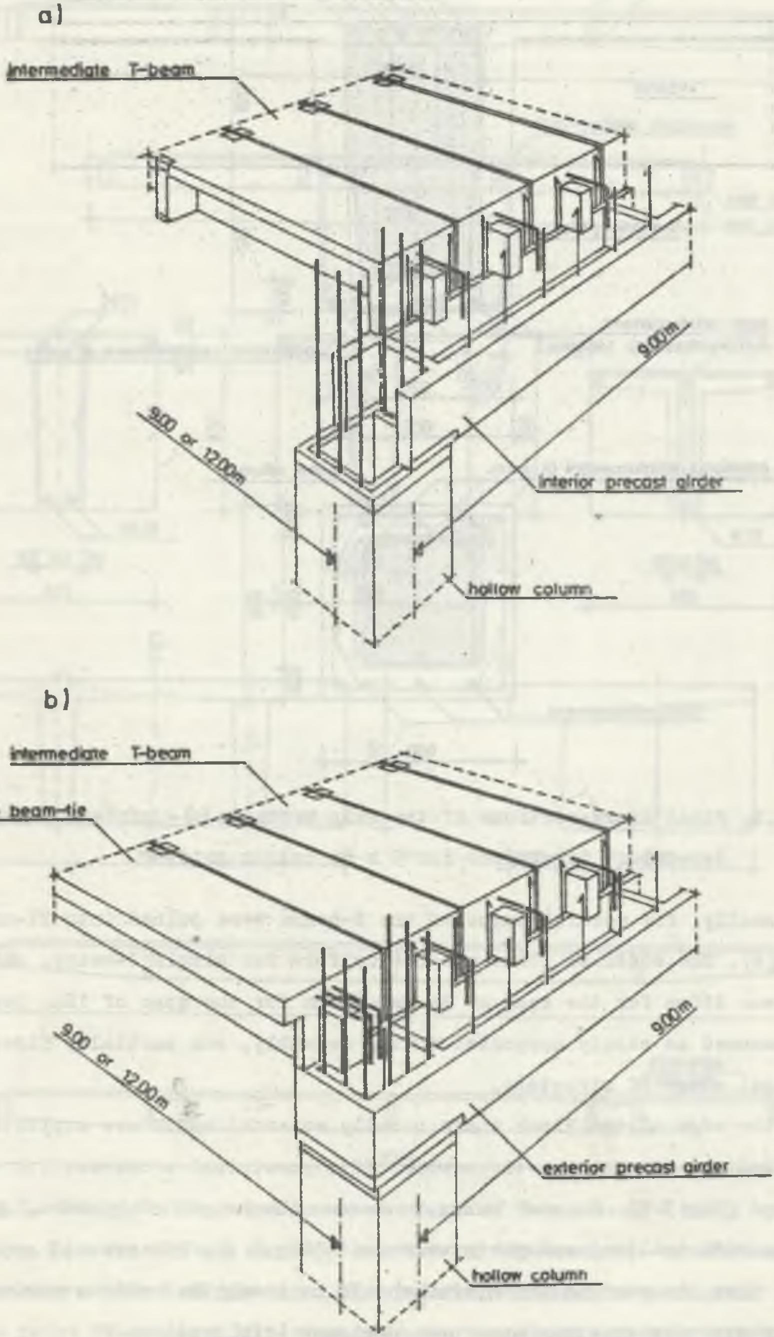


Fig.1. General conception of the structure - arrangement of prefabricates:(a) - interior connection, (b) - edge intermediate connection

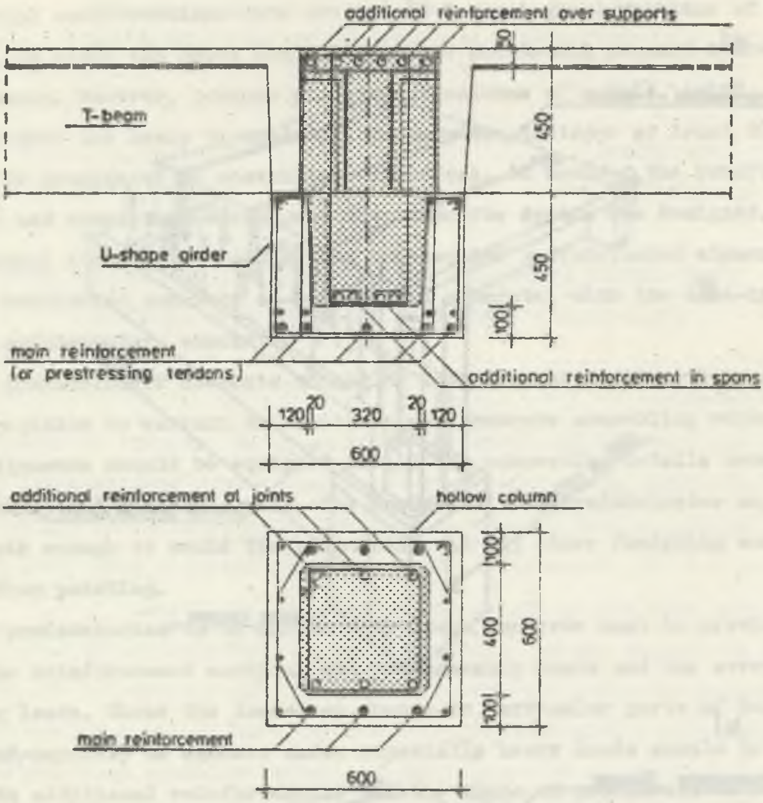


Fig.2. Final cross-sections of the main members: (a) - girder, (b) - column
(exemplary dimensions for 9 x 9m column grid)

Additionally, for special purposes the T-beams were joined into TT-units (Fig.3 e). The width of 600mm was the uniform for single T-beams, and the depth was 450mm for the span of 9m and 550mm for the span of 12m. Beams were assumed as simply supported during assembly, and partially fixed in the final stage of structure.

At the edge of the floor where usually external walls are supported or suspended the strong beam-tie members of asymmetrical cross-section were proposed (Fig.3 f). In some cases, to lessen the height of girders, the T-beams with inclined end-parts were used (Fig.3 g). For special applications, when the ventilation system should be integrated with structure, the members with openings have been designed (Fig.3 h).

The U-shape girder members were designed as reinforced concrete or

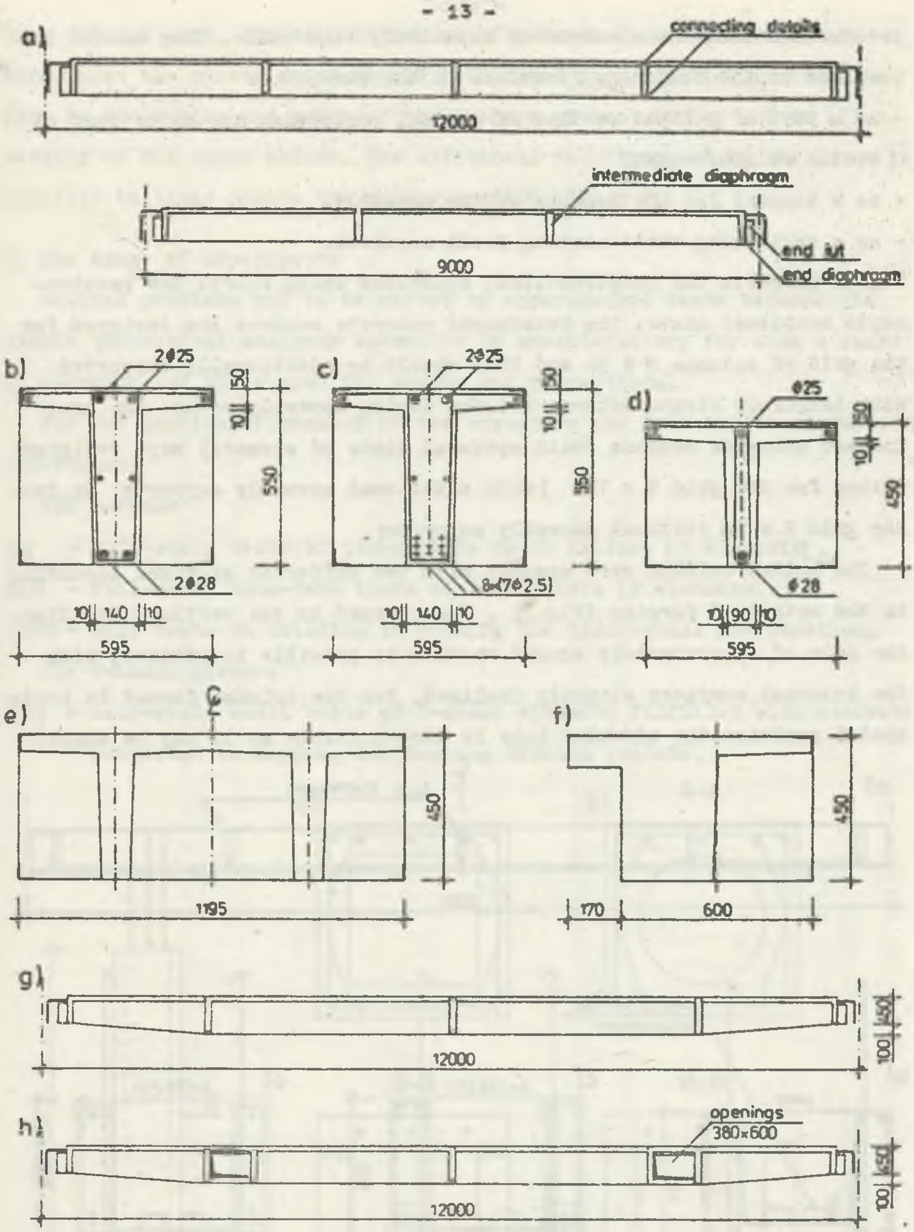


Fig.3. The elevations and cross-sections of T-beams: (a) - basic types of beams, (b) - reinforced concrete section of 12m-beam, (c) - prestressed concrete section of 12m-beam, (d) - reinforced concrete section of 9m-beam, (e) - joint TT-members, (f) - edge beam-tie member, (g) - T-beam with inclined end-parts, (h) - member with openings for ventilation system

prestressed concrete elements of relatively thin walls. They should be prepared to the following functions in the structure:

- as a part of a final section of girder, containing the major part of bottom reinforcement,
- as a support for the T-beams during assembly,
- as a shuttering while casting fresh concrete.

Fig.4. presents the constructional solutions which fulfil the requirements mentioned above: the reinforced concrete members are designed for the grid of columns 9 x 9m and they should be additionally supported with temporary struts between columns during assembly works; the prestressed concrete members (with optional kinds of strands) were designed either for the grid 9 x 12m (with additional assembly supports) or for the grid 9 x 9m (without assembly supports).

The hollow columns were assumed with two different sections according to the method of forming (Fig.5) . When formed in the vertical position the hole of approximately square section is possible to achieve, with the internal surfaces slightly inclined. For the columns formed in horizontal position the circular hole is more suitable as it may be shaped

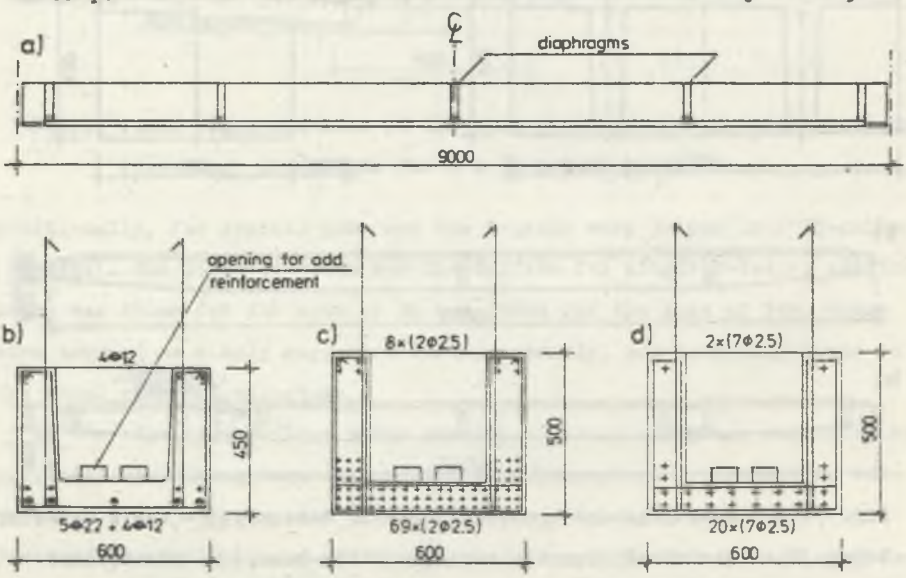


Fig.4. The U-shape girder prefabricates: (a) - longitudinal section, (b) - section of reinforced concrete element, (c) , (d) - sections of pre-tensioned elements

by a tubular core. The main column reinforcement running continuously throughout the girder joint should be located in particular position to pass by the bottom and walls of the U-shape precast member and to allow setting of the upper column. The additional reinforcement at the joint is possible to place inside the hollow section (Fig.2 b).

4. The Range of Experiments

Several problems had to be solved by experimental tests because the simple theoretical analysis seemed to be unsatisfactory for such a scale of elements and their specific shapes and connections.

For the particular members of the structure the following tests were undertaken:

for T-beams

(i) - full-scale tests of 12m-members up to failure (3 elements),

(ii) - full-scale long-term tests of 12m-members (2 elements),

(iii) - site tests in building to clarify the transversal co-operation,

for U-shape girders

(iv) - half-scale model tests of U-shape elements fulfilled with concrete, subjected to hogging and sagging bending moments,

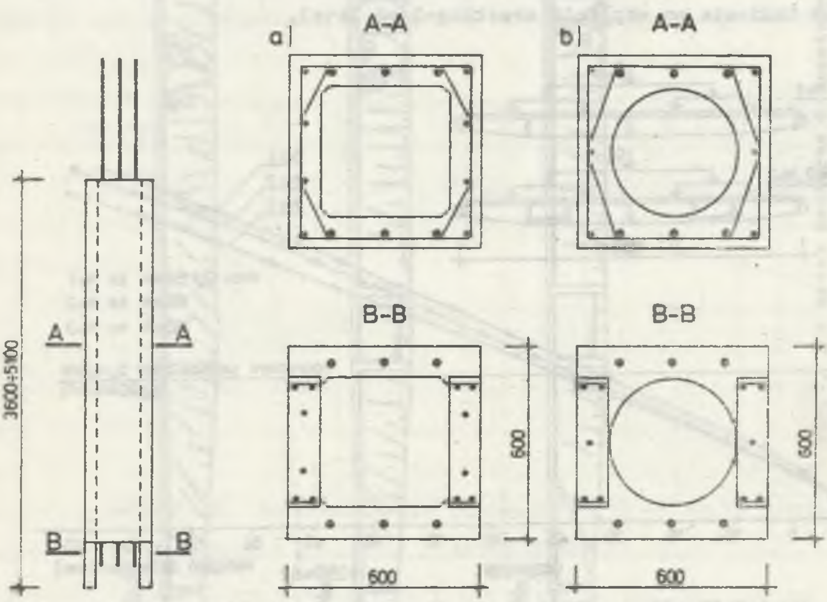


Fig.5. The column precast members with two kinds of hollows: (a) - usually for the vertical casting, (b) - for the horizontal casting

(v) - full-scale tests of U-shape pre-tensioned member subjected to symmetrical and asymmetrical loads,

for hollow columns

(vi) - half-scale model tests of hollow precast members and of composite elements with fulfilled core.

5. Tests of T-beams

The tests were undertaken for the most complicated elements of 12 metres span: solid beams with inclined end-parts and similar beams with openings (steel frames around the openings were built-in). The elements were made from ordinary concrete (approximately C20), with controlled compression strength in the range from 21.3MPa to 23.9MPa. Flexural bottom reinforcement was from high-bond bars of Ø28mm (see Fig.3 b), and stirrups from plain wires Ø6mm. The beams were formed with camber to balance deflections due to self-weight.

Three elements were tested under instantaneous load: four equal forces were used as an equivalent uniform load (Fig.6) . All the elements had several initial micro-cracks from shrinkage of width less than 0.05mm. These cracks resulted in the shape of the load/deflection curves which did not indicate an explicit cracking-load level.

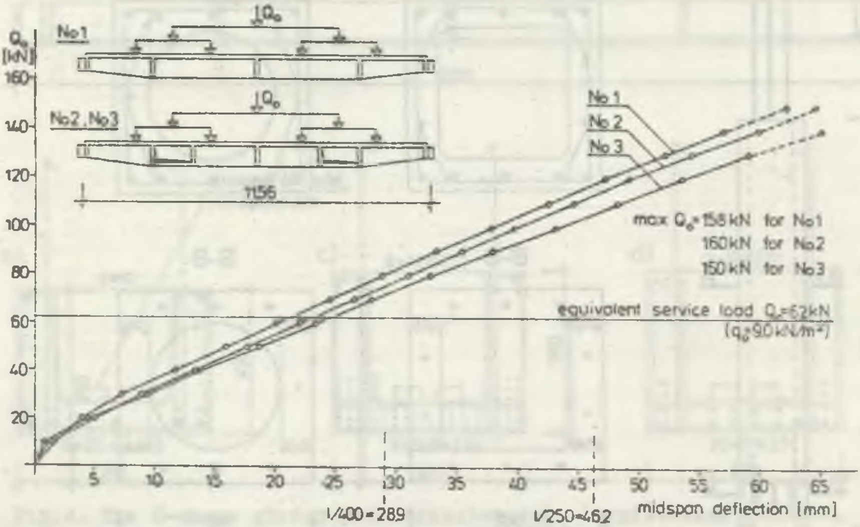
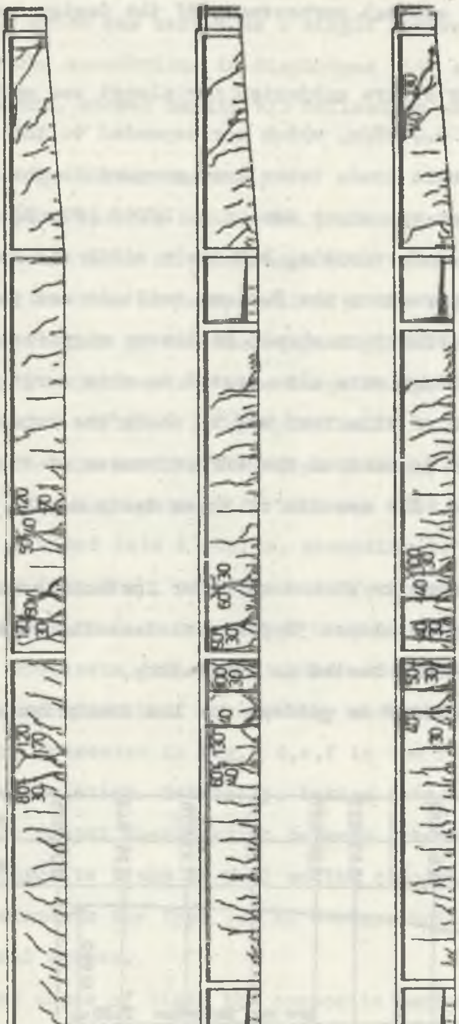


Fig.6. Load/deflection relations in the prototype T-beams tested as simply supported, subjected to first instantaneous load (apart from self-weight).



No1

No2

No3

Fig.7. The crack patterns in prototype T-beams No 1, 2 and 3, tested up to failure (numbers denote the load values at the signed ends of main cracks)

The crack patterns (Fig.7) and the observations of T-beams behaviour up to failure confirmed the general correctness of the design and detailing of elements.

The similar two elements were subjected for almost one and half a year to the long-term load of 5.4 kN/m, which corresponded to the service load of 9.0 kN/m^2 (characteristic loads taken into account in the design). The total long-term deflection was about 44mm,i.e. L/263 (Fig.8) . The initial micro-cracks became more visible, but their width did not exceed 0.1mm. In the completed structure the T-beams built-in are partially fixed in girders so the deflection should be lessen significantly.

The beams without openings were also tested in site during the erection of building. The aim of this test was to check the behaviour of beams with fixed ends and to control the effectiveness of transversal connections between beams. The results of these tests may be described as follows:

- deflection of single beams in structure under instantaneous imposed load of about 6.0 kN/m was almost 35 per cent less than the deflection of simply supported T-beams tested in laboratory,
- the end-parts of beams fixed in girders did not demonstrate any visible

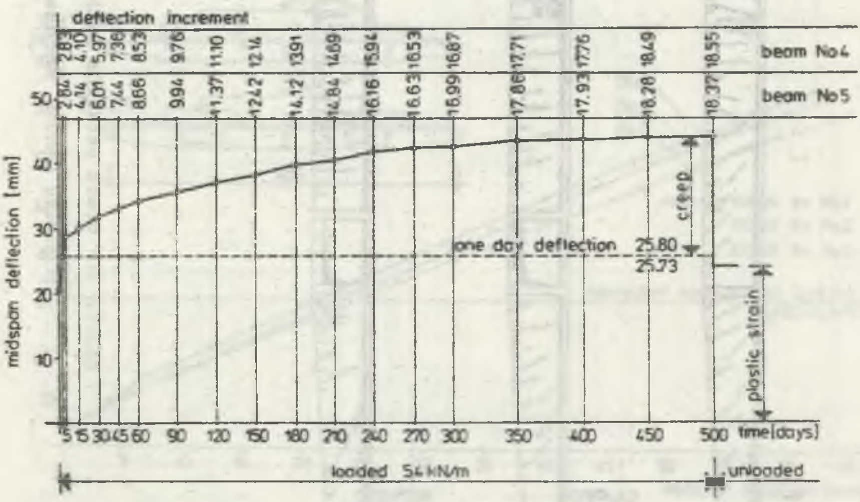


Fig.8. Long-term deflection of uniformly loaded T-beams No 4 (without openings) and No 5 (with openings).

cracks in ribs or in plates,

- the same beam which was tested as a single member of a floor slab, when joined by welded connections in diaphragms with adjacent beams, and loaded as before, showed hardly 1/3 deflection of the single member.

6. Tests of U-shape Girder Members

These tests were carried out in two phases for reinforced concrete models. The initial tests of wide range were devoted to the problem of co-operation of the thin precast shell with the cast-in-place concrete core [3].Many questions of the load-capacity, deflection and cracking were clarified by experiments on the large number of half-scale specimens of the uniform size b/h/L = 200/300/2400mm.

The precast U-shape members were from ordinary concrete of approximate grade C20; the fine aggregate up to 10mm was used. The total number of 101 specimens were divided into 6 series, according to the particular shape of precast elements (Fig.9 a), with three different reinforcement percentage (Fig.9 b).59 specimens were subjected to the instantaneous loading. The second part of specimens (42) were tested under long-term uniformly distributed load, and after half a year they were loaded up to failure. Some results are presented in Fig.9 d,e,f in the form of plots for the force/deflection relation. Generally, taking into account the load-capacity and the proper co-operation between precast and cast-in-place parts of the composite beams as well as the constructional properties of prefabricated elements the type (D) of U-shape units has been selected in all the stuctural system.

In the second phase of tests the composite members were more complicated: they consisted from U-shape units and small precast elements, which imitated precisely the ends of T-beams supported on the girder [2]. To check the behaviour of the final composite member subjected to hogging as well as sagging bending moments the models were tested in two positions (Fig.10 a). All the three types of models (A, B, C) had the same main reinforcement from 8 high-bond bars of Ø16mm. The skin reinforcement in precast U-shape elements was from plain wires Ø4.5mm. The precast parts were from ordinary concrete (approx. grade C20) and cast-in-place concrete was almost two grades weaker (approx. C12).

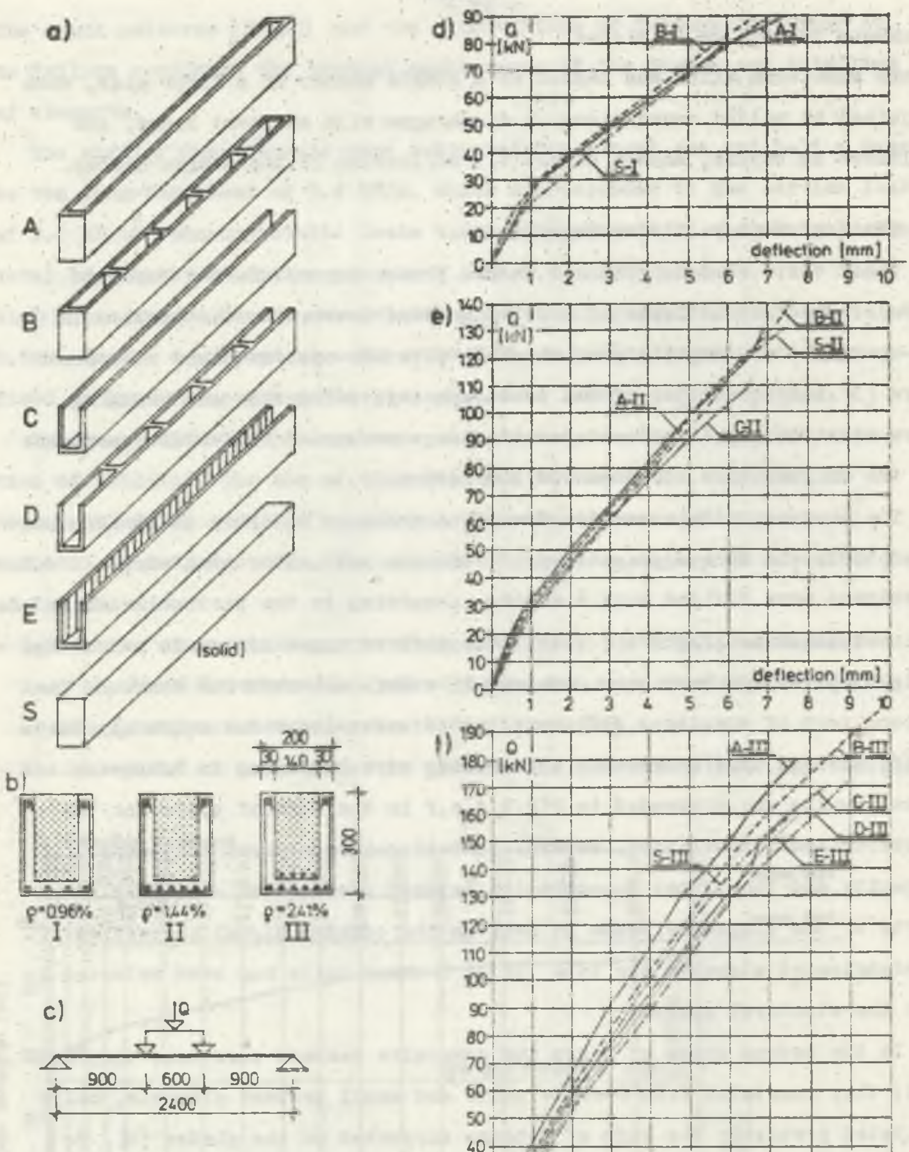


Fig.9. Outline of the first-phase model tests of composite members formed in U-shape precast shells: (a) five types of precast units signed A to E and comparative solid members S, (b) cross-sections with different reinforcement, (c) scheme of loading, Results of tests - the curves of the force to midspan deflection relations: (d) for weak reinforcement, (e) for medium reinforcement, (f) for strong reinforcement (percentages equivalent for ordinary steel)

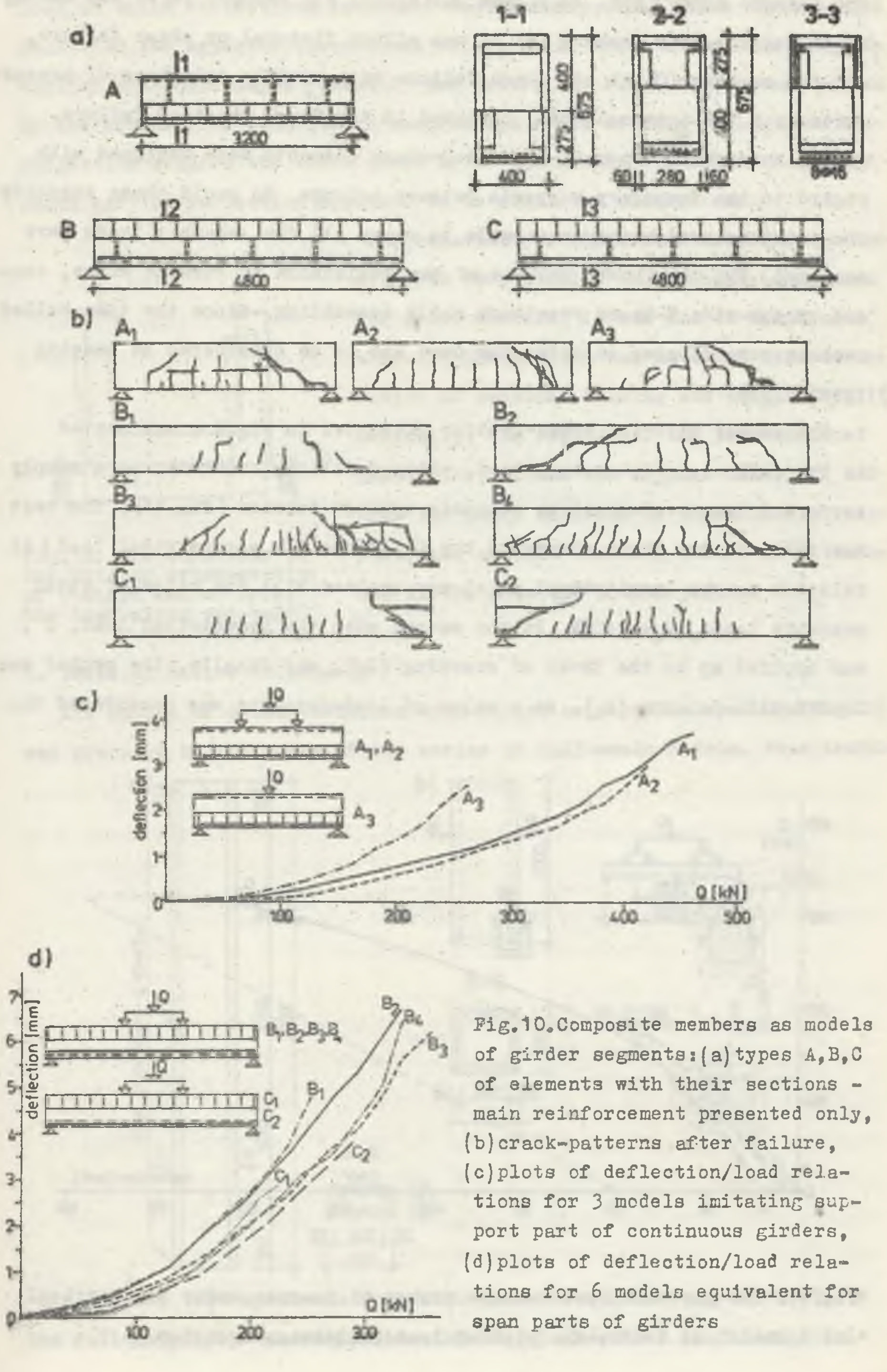


Fig.10.Composite members as models of girder segments:(a)types A,B,C of elements with their sections - main reinforcement presented only, (b)crack-patterns after failure, (c)plots of deflection/load relations for 3 models imitating support part of continuous girders, (d)plots of deflection/load relations for 6 models equivalent for span parts of girders

The failure forms (Fig. 10 b) were different: for members (A) it was mainly shear failure, for members (B) it was either flexural or shear failure, and for members (C) it was shear failure with visible splitting of precast parts from the internal core, observed in the final phase of failure.

The reinforced concrete precast U-shape elements were designed with regard to the temporary supports between columns. To avoid these supports the pre-tensioned elements capable to carry all the assembly loads were designed. The additional problem of the resistance to torsion arose, caused by one-side T-beams reactions while assembling. Since the thin-walled members were of open sections the case had to be considered as warping torsion [5].

The member with the cross-section presented in Fig.4 c was tested in the full-scale laboratory test, without filling concrete, as a simply supported beam restrained on supports against torsion (Fig.11). The test was divided into three steps: in the first one the asymmetrical load (in relation to the longitudinal axis) was applied till the value of total assembly loads, $Q_a = 140$kN. In the second step the symmetrical load, Q, was applied up to the level of cracking (Q_f), and finally, the member was loaded till failure (Q_u). As a value of load-capacity was considered the

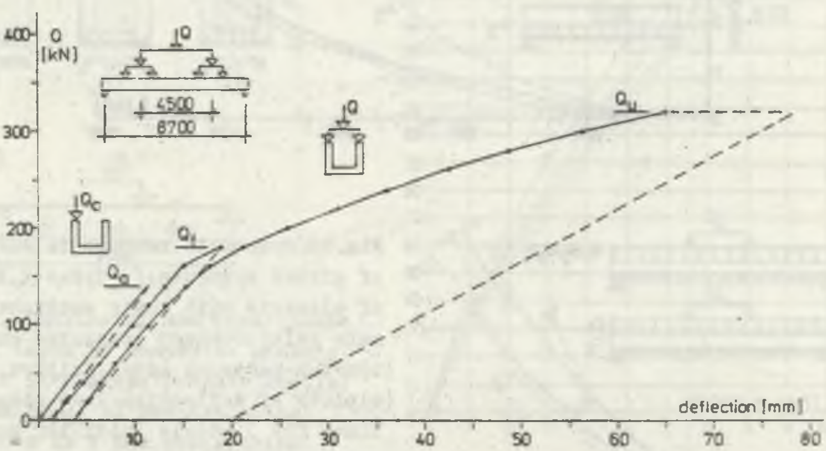


Fig.11. The pre-tensioned U-shape member of 9m-span under asymmetrical and symmetrical loads; the plot of load/deflection relation

load at which deflections increased continuously; this value corresponded well with the expected theoretical value, while the cracking was slightly earlier than calculated (about 15 per cent). The final failure was caused by the crashing of concrete in compression zones of thin walls. When the deflection reached the value about L/100 the member was relieved and the major part of deflection appeared to be still the elastic one.

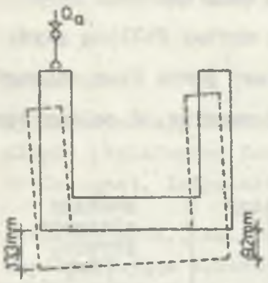


Fig.12. The behaviour of the midspan cross-section of U-shape member under the load along one wall

The behaviour of the member subjected to torsion was very similar to the behaviour known for solid members; it was due to diaphragms that all the section was involved into co-operation at combined bending and torsion (Fig.12). Generally, the results of the pre-tensioned member test showed the regular behaviour and only the small addition of the ordinary reinforcement against cracking should be introduced in the side and bottom plates.

7. Tests of Hollow Columns

The choice of column sections with square or circular openings (Fig.2b) was preceded by the tests of two series of half-scale models. From techni-

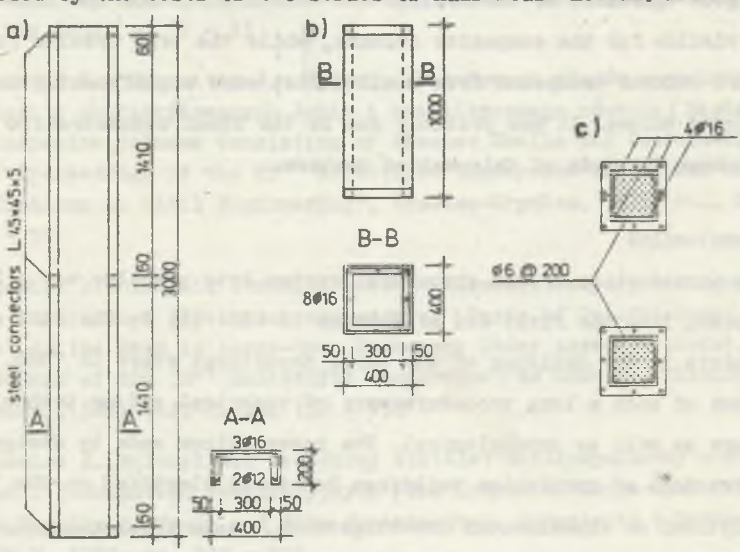


Fig.13. The test specimens for hollow columns: (a) - C-shape element for the full height, (b) - short hollow element, (c) - sections of filled models

cal reasons the hollow precast members were formed from smaller components joined by welding of special connectors. In the first series the C-shape elements were used for the total height of the model (Fig.13 a); three empty columns and two filled with concrete were tested. The precast parts were from the high-strength concrete (approx. grade C35) and the concrete in core was of approximate grade C20. In the second series the closed hollow members were used, but of height 1m only and they were joined into the full-height model with the strong mortar filling gaps; two empty and two filled models were tested (precast parts from concrete grade C30 and cores from concrete C20). The basic results of column tests are as follows:

types of column models		average load-capacity of column at axial compression, [MN]		average ultimate strain, [‰]
		theoretical	tested	
columns compound from two C-units	empty	2.24	1.57	0.69
	filled	3.81	3.92	0.82
columns compound from short hollow units	empty	1.98	1.48	0.71
	filled	3.76	3.66	0.78

The good agreement of theoretical and test results for the load-capacity was visible for the composite columns, while the test results for thin-walled columns (compound from small units) were significantly lower than computed values. It was probably due to the local concentration of stresses near the ends of thin-walled members.

8. Conclusions

An introduction of the structural system into practice was a long process, from the first use of T-beams in 1974 [6] to the full use of all elements in the building of the large department store in 1988. The reason of such a long procedure were of technical and/or technological nature as well as psychological. The reservations made by designers or contractors of particular buildings had to be clarified on the basis of analytical or experimental investigations. These investigations, particularly from experimental area have been described in this report.

The first large 3-storey building with floor-slabs built from T-beams of 12m span has been in constant use for over 15 years and the periodical observations confirmed the structural and functional effectiveness of the solution in spite of the changes inside the building. Similar observations on six other 3- to 5-storey buildings allowed for the positive result of general assessment.

Nowadays, the studies and design for the use of the system in trade or industrial stores, with service loads of 15 kN/m^2 are in progress.

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MULTI-STOREY STRUCTURAL SYSTEM CONSISTING OF PREFABRICATED THIN-WALLED ELEMENTS AND CAST-IN-PLACE CONCRETE

Summary

The report deals with the idea, tests and first applications of composite skeletal structure for municipal buildings, e.g. department stores, schools, libraries. The large spans (9 to 12 m) in both directions, the big loads (5 to 15 kN per m^2), the high storeys (4.5 to 6 m) and lack of bracing walls for buildings of 3 to 5 storeys were the main assumptions in this solution.

To avoid heavy scaffoldings and shuttering precast R.C. and/or P.C. members have been assumed. However, prefabricated beams or columns of full sections were too heavy to assembly, particularly when buildings were large in the plan. Therefore, the composite structure consisting of the thin-walled prefabricated elements and cast-in-place concrete has been designed. Three basic types of precast units were proposed and tested in full scale:

- R.C. or P.C. T-beams of 9 and 12 m span,
- pre-tensioned U-shape members for 9 m girders,
- hollow R.C. column members for the full height of storey.

The particular members of the structure, after laboratory or site tests, have been introduced step-by-step in practice and some modifications were done due to specific requirements, especially for the integration of structures and installations.

Keywords: composite construction (concrete to concrete) , cracking, deflection, precast concrete, prestressed concrete, reinforced concrete, skeletons, warping torsion.

SYSTEM KONSTRUKCYJNY WIELOKONDYGNACYJNEGO SZKIELETU ZŁOŻONEGO Z CIENKOŚCIENNYCH PREFABRYKATÓW I BETONU UZUPEŁNIAJĄCEGO

Streszczenie

Opracowanie przedstawia koncepcję, badania i pierwsze zastosowania zespolonej konstrukcji szkieletowej dla budownictwa miejskiego, np. domów towarowych, szkół, bibliotek. Głównymi założeniami w tym rozwiązaniu były duże rozpiętości w obydwu kierunkach 9 do 12m, duże obciążenia od 5 do 15kN/m^2, wysokie kondygnacje do 6m i brak ścian stężających dla obiektów do 5 kondygnacji. Niektóre wyniki badań w skali półtechnicznej i pełnej przytoczono w pracy.

КОНСТРУКЦИОННАЯ СИСТЕМА МНОГОЭТАЖНОГО КАРКАСА СОСТОЯЩЕГО ИЗ ТОНКОСТЕННЫХ ЭЛЕМЕНТОВ И ЗАМОНОЛИЧИВАЮЩЕГО БЕТОНА

Резюме

В статье представлена идея, испытания и первые применения сборного каркаса в городском строительстве, как например в универмагах, школах, библиотеках. Главными основами этого каркаса были большие пролёты 9-12м, большие нагрузки от 5 до 15кН/м^2, высокие этажи до 6м, отсутствие диафрагм жёсткости до 5 этажа. Некоторые результаты полутехнических и технических испытаний представлены в работе.