A R C H I T E C T U R E C I V I L E N G I N E E R I N G E N V I R O N M E N T
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STRUCTURAL RESPONSE OF PRECAST BUILDINGS UNDER ORDINARY AND ACCIDENTAL LOADS IN RESEARCH WORKS OF PROFESSOR ANDRZEJ CHOLEWICKI

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Abstract

The paper presents the basic achievements of many years of scientific work of Professor Cholewicki on: load bearing capacity and deformability of the vertical joints in large panel buildings, the calculation methodology of shear walls, the impact of floor integrating character in the horizontal transfer interactions, the efficiency of the shear connections in composite precast concrete structures, design concepts skeletal precast RC structures in accidental situation (progressive collapse) and the principles of design and diagnosis of buildings subjected to paraseismic soil tremors in mining areas.

Streszczenie

W pracy przedstawiono podstawowe osiągnięcia wieloletniej pracy naukowej Profesora Cholewickiego w zakresie: nośności i odkształcalności złączy pionowych w budynkach wielkopłytowych, metodyki obliczeniowej ścian usztywniających, wpływu integrującego charakteru tarczy stropowej w przenoszeniu oddziaływań poziomych, efektywności zespolenia w prefabrykowanych konstrukcjach typu beton-beton, koncepcji projektowania szkieletowych konstrukcji żelbetowych z uwagi na możliwość wystąpienia sytuacji wyjątkowej (katastrofy postępującej) oraz zasad projektowania i diagnozowania budynków poddanych oddziaływaniom wstrząsów parasejsmicznych na terenach górniczych.

Keywords: **Precast building; Shear wall; Joints; Diaphragm action; Progressive collapse; Soil tremor; Composite action.**

1. LOADBEARING CAPACITY AND DEFORMABILITY OF VERTICAL JOINTS IN STRUCTURAL WALLS OF LARGE PANEL BUILDINGS

Professor Cholewicki has carried out a study aimed at formulation of principles for estimation of the shear bearing capacity and stiffness of vertical joints [1]. The following characteristic phases in behaviour under shear forces can be distinguished: phase I – joint as monolithic structure (bond is not damaged); phase II (when the bond is damaged). These phases decide about joint bearing capacity and deformability as well as effects of the behavior of the whole shear wall.

For calculation of the bearing capacity of shear-key joints below given formula have been proposed by the Professor.

The summary of theoretical considerations and experimental results from several testing laboratories here in Europe was published in [1] (see Fig. 1). The study was also the background reference for draft guide [2] for the design of large panel connections elaborated by CEB (European Concrete Committee). Formula for design resistance derived by Professor of [1] and introduced in CEB document [2] was:

$$R_{jVd} = \frac{1}{\gamma_d}\left[\beta_1 A_{key} f_{cd} + \beta_2\left(A_s f_{yd} + N_d\right)\right] \le 0{,}3 A_j f_{cd}$$

where:

$\beta_1 \beta_2$ – coefficients for expressing the contribution to the joint resistance of the in-situ concrete and of the transverse reinforcement and the normal compression force (N_d) acting in the joint,

A_{kej} – effective shear-keys area,

A_j – the longitudinal cross sectional area of the joint

γ_d – complementary partial safety factor,

f_{cd} – design strength of concrete in the joint,

f_{yd} – design strength of steel

The formula for shear stiffness of vertical joints, derived by Prof. Cholewicki of [1] (Fig. 2), has been given in [2].

2. METHODS OF ANALYSIS AND PARAMETRIC STUDIES OF SHEAR WALLS

Among several approaches which may be applied for idealization of shear wall structures, the author has particularly emphasized a continuous medium method and finite element method. The application of both of these methods requires some knowledge of principles and formulae, according to which the calculation stiffnesses of different type of coupling connections are determined. The term coupling connection includes all kinds of constructions which interconnect the vertical wall beams. The most typical connections are rows of lintels and vertical joints (in a precast structure).

The coupling function is also satisfied by fragments of floor diaphragms or tie beams, which behave similarly to so-called local coupling connections.

Professor Andrzej Cholewicki has developed in early 70s pioneer approaches – linear and nonlinear ones done with finite element methods (FEM) (Input data has been prepared personally by Professor at that time it was done on perforated cards). It should be

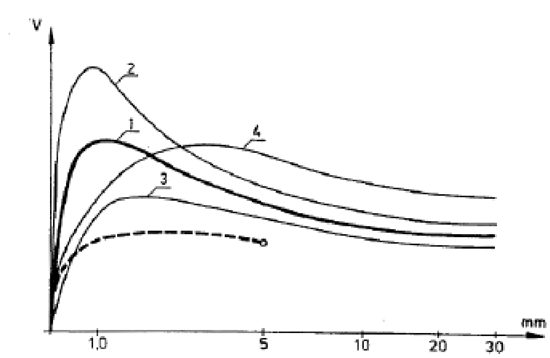

Figure 1.
Relation V(u) for joints with the same reinforcement ratio, according to [1] (and recommended in [2]), 1, 2, 3, 4 variation of main parameters of N_d force.

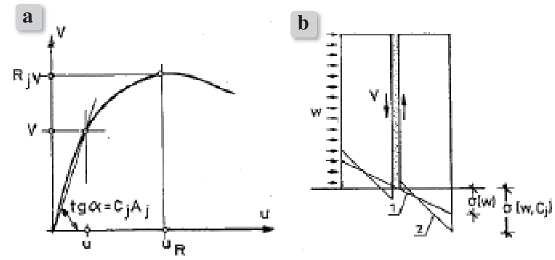

Figure 2.
The joint stiffness Cj (a) and its influence (b) on the distribution of stresses at the bottom cross-section
1 – neglecting deformability of the vertical shear joints
2 – taking it into account

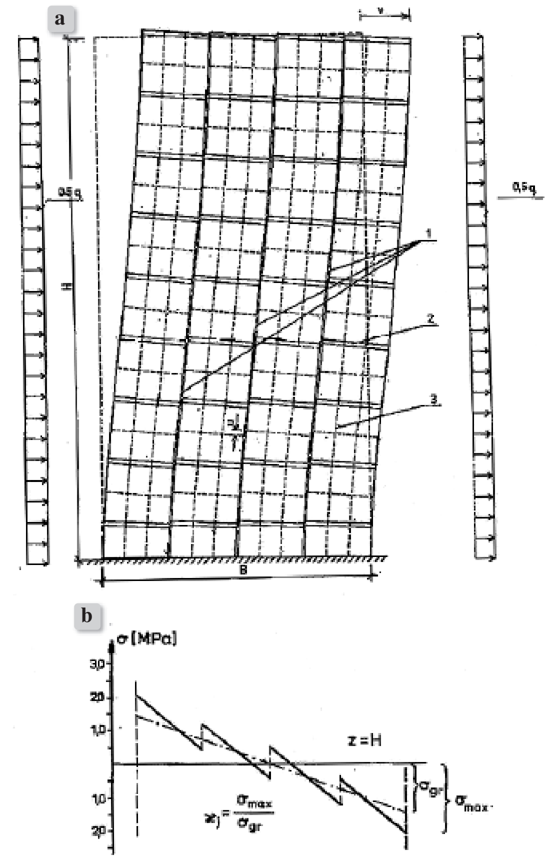

Figure 3.
Model of a shear wall made of large panels, analysis with account of nonlinear characteristres of vertical joints (at that time pioneer analysis in the world scale)
a) displacements
b) diagram of stresses σ at the base
1. vertical joints
2. horizontal joints
3. subdivision of the wall into finite elements as used by the author for analysis by means of program GENFEM

underlined that it was the period when FEM was at beginning phase particularly as a tool for non-linear approaches. A good coincidence of facts was the possibility of cooperation of Professor Cholewicki with famous top world specialists like Professors H. Petersson and occasionally R. W. Cloungh.

Another direction of studies was three dimensional analysis of multistory building structures. The structural walls situated along both main directions of the building (X and Y directions), mutually connected in a monolithic way (in cast-in-situ buildings) or by vertical joints (in large panel buildings), or by o system of lintels together with floor diaphragms, constitute an effective stiffening system which resists lateral load of different natures, including also ones appearing due to accidental loads.

Professor A. Cholewicki developed the methods of analysis according to continuous medium model approach (CMMA) and initiated elaboration of computer systems here in Poland second direction of his activity within this area were pioneer studies on the behaviour of shear walls done mostly with the help of finite element methods (FEM). In early years 70 ties the analysis initiated by Professor were new in the world scale. Full information about those investigations has been given in [3] [4].

The development of calculation methods aims to treat these structures as integrated three-dimensional stiffening systems analyzed with computers. Despite considerable progress in the field of methods themselves and technical equipment of computer centers, as well as growth of staff qualifications, the simplified approaches in analysis of three-dimensional behaviour of wall structures are still applied and so will be the nearest future. The simplified approaches imply the adaptation of the so-called model of dissected wall assemblies, whose basic elements are single walls or wall assemblies, and calculations of which may be carried out either with the aid computers (including also mini-computers) or completely without this equipment.

Parametric studies of shear walls with opening rows have shown general agreement of the results according to the continuous medium and the finite element methods.

A numerical study of the behaviour of single coupled shear walls with allowance for non-linear relationships V`(u) of lintels (where V`= unit shear force and u = vertical shear displacement) gives the answer to the question of the consequences of elastic-plastic behaviour of the lintels.

Similar study of large panel walls whose vertical joints are characterized by the non-linear relationship V(u) illustrates as e.g. shown in Fig. 3 the consequences of plastic displacement of vertical joints for the changes of normal stresses.

In coming years Professor and his group have developed a "correction method" allowing to verity the results obtained under assumption of elastic behaviour of model [5].

3. FLOOR DIAPHRAGM ACTION CONSIDERATIONS AND DESIGN RECOMMENDATIONS

The stability of precast concrete buildings is provided in two ways. Firstly the horizontal loads due to wind are transmitted to shear walls or moment resisting frames by the floor (or the roof). In most instances this consists of individual precast concrete hollow core units, 1.2 m in width, as shown in Fig. 4. Secondly, the reaction forces resulting from the floor at each level are transmitted to the foundation. Where the distance between the shear walls is large, say more than 6 to 8 m, the floor has to be designed as a plate, or so called "diaphragm", which must sustain shear forces and (frequently) bending moments. To achieve this, a "ring beam", or series of "ring beams", as shown in Fig. 4, is formed around the precast floor units to effectively clamp slabs together and to ensure the diaphragm action.

Precast pre-stressed hollow core units are among the more advanced structural floor systems for all kinds of buildings. The reason for this lies not only in the production technology, which is nearly fully automated, but also in other features such as optimum use of materials, slenderness of the construction, environmental friendliness, etc. Compared to plain concrete floors, hollow core floors can save 50% concrete and 30% steel for the same performances.

Because of the wide use of the product, and the creation of new markets and applications, much research work has been carried out in the past and is still going on, e.g. concerning the transfer of prestressing at the slab end, continuous supports, non-rigid supports, diaphragm action, composite action with the supporting beam, large openings, seismic action, non-static loading etc. The FIP Commission on Prefabrication published in May, 1998 a Guide to Good Practice on "Composite floor structures", in which the interaction between floors and toppings, or between floors and their supporting beam, is dealt with.

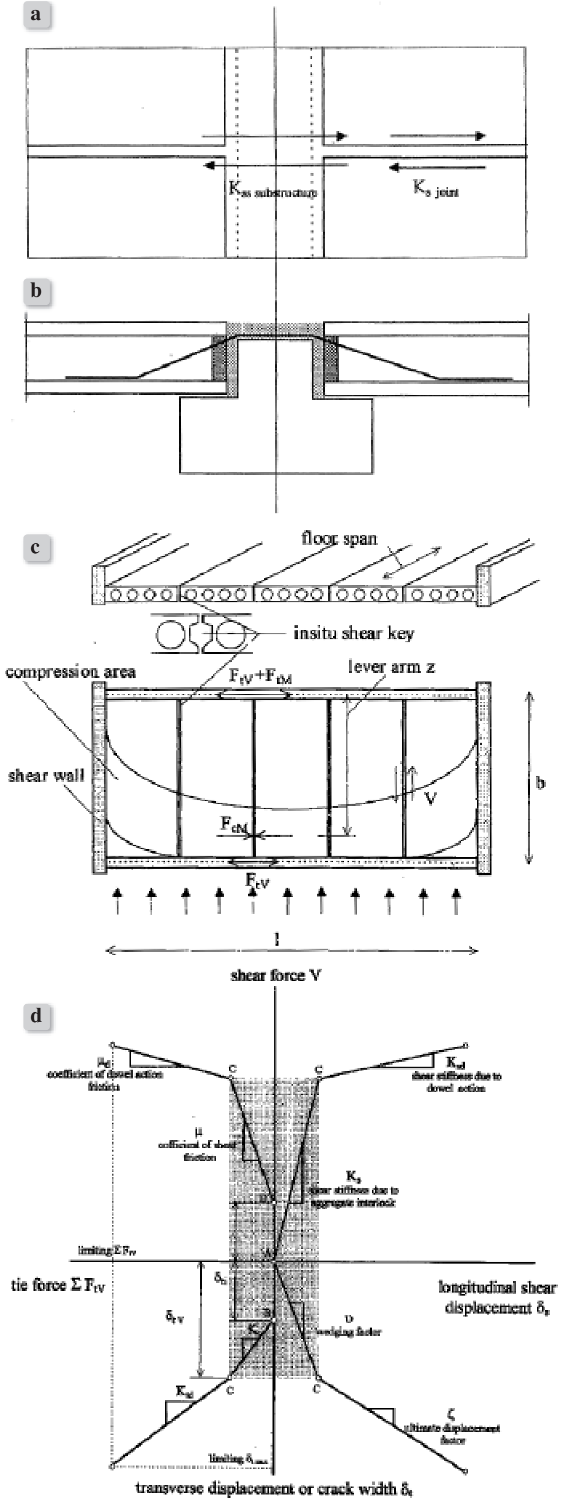

Figure 4.
Calculation model of a precast floor diaphragm [7] and [6] a) b) beam fulfilling the function of a shear member c) plan of a floor diaphragm d) constitutive relationships between shear force V, transverse tie force ΣF_{tV}, longitudinal slip δ_S and transverse displacement δ_t

Professor Andrzej Cholewicki was one of the main authors of the of fib document [6] and he contributed particularly to:

- formulation of the principles of shear transfer mechanism through the longitudinal connections of HC precast units,
- evaluation of the effectiveness of tying reinforcement,
- elaboration of calculation model and formulae according to shear wedging / shear friction resistance theory.

4. COMPOSITE ACTION OF PRECAST FLOOR BEAMS

Precast beams should be designed as composite with the floor to enhance the flexural and shear capacity, fire resistance and stiffness [7]. The main advantage of a composite beam structure is that it permits less structural depth for a given load-bearing capacity. The breadth of the compression flange can be increased to the maximum permitted value, as in monolithic construction. For composite action with hollow-core floors, the collaboration of those ones can be ensured through the concrete filling of the cores. This comprises only the top and bottom flanges of the slab.

Both types of shear connections, i.e. of the horizontal one and of both vertical ones, (Fig. 5) should be treated as shear deformable media. The effects of those media for the behaviour of the whole composite system have been the objective of research studies initiated and conducted by Professor A. Cholewicki. Several papers and contributions to domestic and international conferences described his approach and his research group, they were also presented in fib Bulletin [8]. The most important result was the developed philosophy that design of those precast floor beams should not be considered according to principles of a homogenous structures applied in common cast-in-situ structures but as the composite beams, with a controlled model of interaction. This control is to be done with the help of so called $\frac{\alpha L}{2}$ value [9] see below

$$\frac{\alpha L}{2} = \frac{L}{2}\sqrt{\left(\frac{1}{E_{C1}A_1} + \frac{1}{E_{C2}A_2} + \frac{a^2}{E_{C1}I_1 + E_{C2}I_2}\right)K_s}$$

E_{C1}, E_{C2} – respectively, concrete elasticity modulae in parts ① and ②

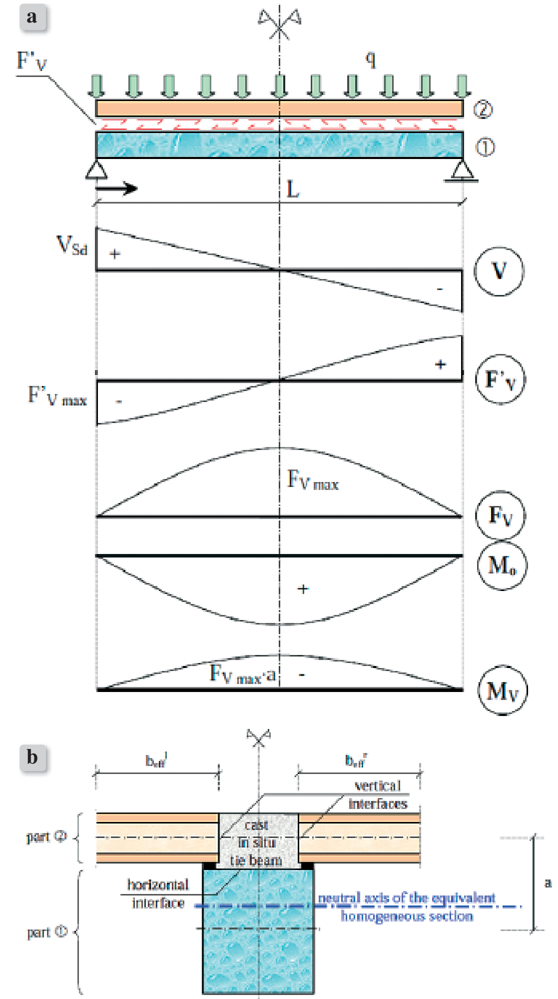

Figure 5.
Two-beam model of a composite simply supported beam
a) diagrams of shear forces and moments
b) cross section, positions of horizontal and vertical interfaces (joints)

A_1, A_2 – respectively, cross section areas of parts ① and ②
I_1, I_2 – respectively, moments of inertia of parts ① and ②
a – distance between the central points of parts ① and ②
L – span of the beam
K_S – shear stiffness (see chapter "Shear stiffness estimation")

The message sent to practice communicated: "do not attempt to get model of a homogenous structure when you deal with a precast set of interacted members". This statement has a great importance because the precast composite systems are growing family structures.

5. DESIGNING REINFORCED-CONCRETE FRAME OF BUILDINGS TO LIMIT THE RISK OF PROGRESSIVE COLLAPSE (ROBUSTNESS CONSIDERATIONS OF FRAMED BUILDINGS)

Robustness of structures – a forgotten design target? Engineering structures may react on high or unplanned load scenarios in considerably different manner. Some remain nearly free of damage, others are affected by loss of their load-bearing capacity. The property of structural survival with rather limited damage is called structural robustness, defined with respect to a specific action. However, and in opposition to classical structural properties like redundancy or ductility, for robustness neither an exact definition nor any quantification have existed up to now. The present contribution attempts both in engineering-like manner; it explains the gained derivations by example of several structural responses, and draws attention to catalogues and procedures for enhancement of structural robustness.

Following the famous progressive collapse of the Ronan Point building in the UK, a number of regulations were enacted, primarily with regard to multi-storey large panel system buildings and the dangers posed to such structures by gas explosions. These regulations reflect the views of 30 years ago, whereas present-day risks are more varied, and moreover, the framework buildings which now dominate are harder to protect against the effects of local damage to the load-bearing structure. An increasingly common occurrence over the past decade or two has been terrorist attacks, which may – although this need not always to be the case – lead to progressive collapse of a building. A structure may also be subject to other exceptional effects, several of which are addressed in the PN-EN 1991-1-7:2008 Eurocode 1 standard "Actions on structures", section 1-7 "General actions. Exceptional actions."

In the PN-EN 1992-1-1:2008 Eurocode 2 standard "Design of concrete structures" a requirement was laid down to ensure the overall structural coherence of a building (**robustness of structure**), aiming at eliminatinge the risk of progressive collapse in the case of damage to or destruction of one load-bearing element of the building. In the case of framework buildings, which are the subject of the present guidelines, the case is considered of the elimination of one column, around which a zone of defined dimensions is formed (see also Fig. 6).

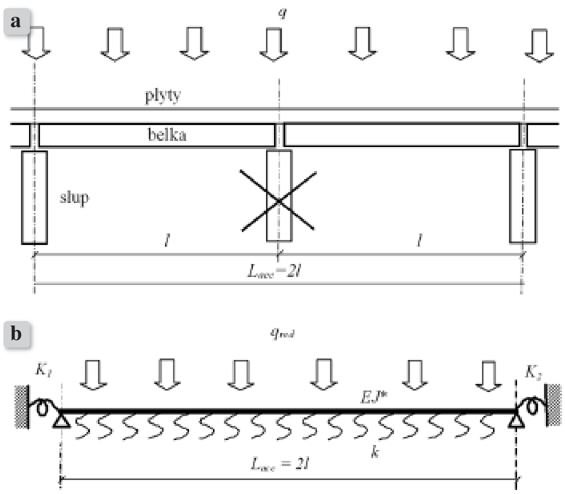

Figure 6.
Calculation model derived by authors of [10] for a precast framed structure with a damaged column
a) side view
b) floor slabs supported on beams and giving also the vertical reactions to the beams

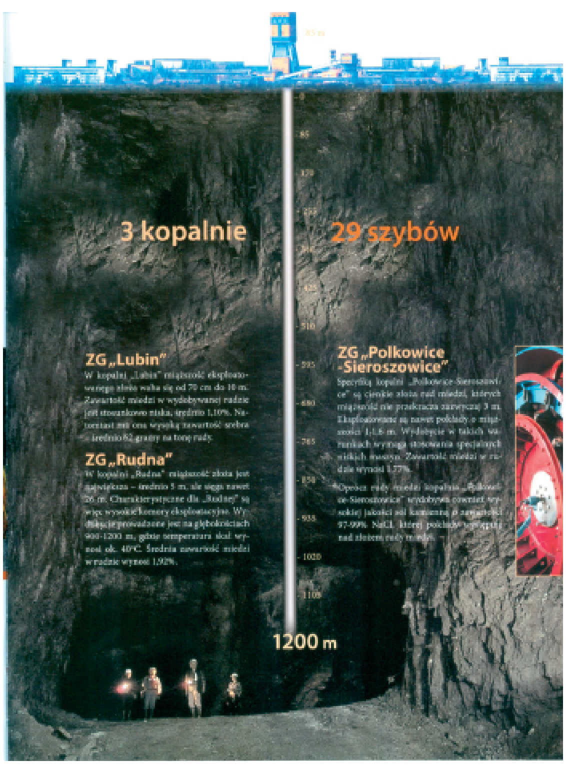

Figure 7.
Soil tremors occurring in the Copper Region of Poland are not easy to be quantified paper (in Polish) „The world of polish copper" KGHM Poland 2008

Through the implementation of appropriate design recommendations a structure can be given features which enable it to survive safely an exceptional situation and its consequences. Fulfilment of this requirement is achieved in accordance with an indirect or direct concept. Detailed explanations of both concepts with respect to monolithic and prefabricated framework buildings are provided in the guidelines [10]. Attention is chiefly focused on the methodology of designing secondary load-bearing structures in accordance with direct concept. An introduction to this part of the guidelines is provided, which concerns possibilities of designing a secondary load-bearing structure for a monolithic construction.

The research works of Professor and his group were focused on methodology for designing secondary load-bearing structures in prefabricated buildings – the bending model (Fig. 6b). This model makes it possible to monitor the status of displacements of the secondary load-bearing structure and to limit those displacements in a way that does not necessitate carrying out costly repairs to the entire building.

The calculation method given in the guidelines [10] is a result of the authors' own research work, and is original even on an international scale. In this method particular attention is given to reserves of load-bearing ability, which come to light when the secondary load-bearing structure of a prefabricated framework construction is analysed. These reserves are discussed, and their use is illustrated by a numerical example.

6. PRINCIPLES OF DESIGN AND STRENGTHENING OF BUILDINGS SUBJECTED TO SOIL TREMORS IN MINING AREAS

In some regions of Poland due to present or former mining exploitation, particularly in Copper Region and Upper Silesian Coal District, soil tremors occure which can be compared to low intensity earthquaqes.

For more than 20 years Professor Andrzej Cholewicki conducted the research works which were aimed at following objectives[11]:

– specific features of building structures subjected to para-seismic excitation,
– soil tremors as the equivalent loading of those structures,
– design principles for multistorey and low rise buildings which should be applied in order to protect those buildings against the effects of soil tremors [see 12],

– strengthening of existing buildings,
– interpretation and implementation of Eurocode 8 recommendations for the buildings protection in view of combination of different actions appearing in the areas of soil tremors and of other kind of accidental effects.

Beside the research activity as mentioned above, Professor was involved in the real examination even of the whole towns, like the one shown symbolically in Fig. 7, in the Copper Region. Several times his presence "on place" and opinions contributed to relax of the occupants frightened by the seismic shock.

7. SUMMARY

The 75th birthday anniversary was the occasion to remind some scientific achievements of Professor Andrzej Cholewicki.

His intensive commitment to the problems of analysis of spatial behaviour of buildings, particularly those built of precast elements, should be emphasized. He published a lot on this subject, consulted about 60 design offices and trained specialists indicating to new opportunities with the use of computer methods.

At international level the following aspects of his work should also be emphasized. For many years he represented Poland in the (former) CMEA Commission "Spatial rigidity of structures", cooperation with the CIB Commission "Bearing walls" and in the *fib* Commission "Prefabrication". Cooperation to that Commission gave him the position of Europeen expert particularly on objectives of three dimensional analysis of building structures and reduction of risk of progressive collapse of precast buildings.

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