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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INFLUENCE OF TYING REINFORCEMENT IN JOINTS ON BEHAVIOUR OF SKELETON PRECAST STRUCTURE IN ACCIDENTAL SITUATION

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A b s t r a c t

This paper deals with finite element modeling of the behaviour of skeleton precast structure in accidental situation. The current study is focused on the influence of the type and position of tying reinforcement in joints on the ultimate capacity and deflection of the secondary load-carrying structure formed due to accidental removal of the internal column. The 2-dimensional finite element model contains two spans of precast prestressed concrete beams supported initially by three precast columns (column in the middle will be removed) as well as slabs. Constitutive material models include nonlinear behaviour: cracking/crushing for concrete, debonding and slipping for interfaces between concrete elements, plasticity for reinforcement. Obtained results are compared with analytical two-beam model.

S t r e s z c z e n i e

Artykuł przedstawia symulację numeryczną zachowania się prefabrykowanej konstrukcji szkieletowej w sytuacji wyjątkowej. Niniejsza praca jest skoncentrowana głównie na wpływie rodzaju i położenia zbrojenia zszywającego w połączeniach na nośność i ugięcie wtórnego ustroju nośnego utworzonego na skutek niezamierzonego usunięcia słupa wewnętrznego. Dwuwymiarowy model MES składa się z dwóch przęseł prefabrykowanego stropu składającego się z płyt i belek sprężonych, podpartego początkowo przez trzy słupy (w dalszej kolejności środkowy słup zostanie usunięty). Materiałowe modele konstytutywne przyjęte w analizie posiadają własności nieliniowe: pękanie/kruszenie dla betonu, poślizg i utrata przyczepności w złączach między elementami prefabrykowanymi, plastyczność dla stali zbrojeniowej. Otrzymane wyniki analiz numerycznych porównano z wynikami według metody dwupasmowej.

K e y w o r d s: **Dynamic; Nonlinear; Precast structures; Progressive collapse; Tying reinforcement.**

1. TYING SYSTEMS TO REDUCE THE RISK OF PROGRESSIVE COLLAPSE

There are three alternative design concepts that may be part of a multi-hazard design approach. The alternatives are a) the design approach; b) the alternate path approach; and c) the specific load approach [1]. The latter two are also defined as direct design approaches. Each design approach is based on assumptions and conditions that offer technical advantages and disadvantages.

1.1. Indirect design approach

With Indirect Design, also called “Tie Force Approach”, resistance to progressive collapse is considered implicitly “through provision of minimum levels of strength, continuity and ductility” through the structure. In the “Tie Force Approach” building is mechanically tied together, enhancing continuity, ductility, and development of alternate load paths. Tie forces are typically provided by the existing structural elements and joints that are designed using conventional design procedures to:

• carry the standard loads imposed upon the structure,

- are designed according to commonly accepted rules (and not directly dimensioned proportionally to the calculated internal forces which appear due to those standard loads).

Application of this method should provide a building with sufficient robustness to survive a reasonable range of undefined accidental actions. The definition of the term robustness is as follows [2]:

structures should be planned and designed so that they are not unreasonably susceptible to the effects of accidents. In particular, situations should be avoided where damage to small areas of a structure or failure of a single element may lead to collapse of major parts of a structure.

The requirements relating to ties with hollow core floors in precast concrete structures can be specified on example of British Standard BS8110 [3]. Those ones are satisfied either by using individual continuous ties provided explicitly for this purpose in insitu concrete strips, or using ties partly in the insitu and partly in the precast components. The structural model is as follows. In the event of the complete loss of a supporting column or beam at a floor level, the floor at this level and the level above must resist total collapse.

The definition of ties connecting the hollow core slabs with the super structure is [4]:

- floor ties – connecting floors over an internal support,
- perimeter floor ties – connecting floors to a perimeter support,
- internal ties - i.e. ties over an intermediate support perpendicular to the span of the floor,
- peripheral ties – ties over a peripheral support.

With a structural concrete topping the indirect tying model has been enhanced, the reinforcement in the topping is usually sufficient to comply with the tying requirement.

1.2. Alternate path approach (APA)

In framed buildings with hollow core slabs the size of local damage is determined usually on the assumption that only one column has become totally ineffective. Then, the alternative bearing system should appear in which the ties projecting from the supporting edges of hollow core slabs fulfil an essential role. The contribution of those ties to the alternative bearing system depends at least on:

- enhancement of the composite structure created by the precast beam on hollow core slabs, whose span has been approximately doubled ($l_{acc} \approx 2l$),
- integration of two slabs, supported on the beam each one from each side, into so-called two – slab members, which ensure the additional supports to the beam after the column has been damaged.

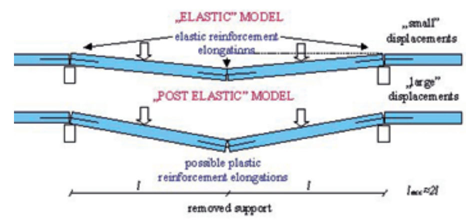


Figure 1.
Possible beam models in accidental situations

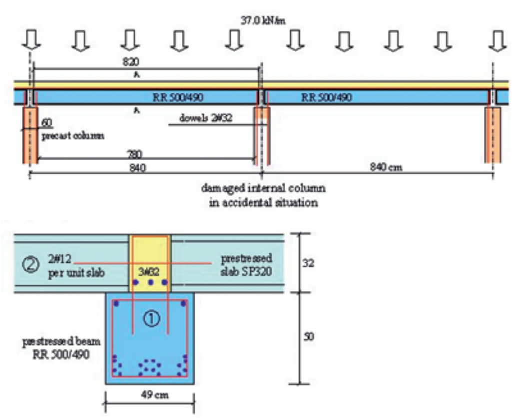


Figure 2.
View of structure a) side view of one span, b) section A-A

Structural topping can magnify both these functions.

According to the above descriptions two models have been distinguished for the analysis:

- an "elastic" one where features are the same as in the case of the permanent situation; the essential difference between the models for permanent and accidental situations resides in doubled span of the beam in the last one – Fig 1a,
- a "post elastic" one for which possibility of occurrence of a large displacement was assumed and a tendency to the so-called membrane action model (in other words appearance of a suspension mechanism) (Fig. 1b) can be considered.

After years of studies by A. Cholewicki and his group the first model seems to be much more realistic and friendly for designing.

A simplified so-called two-beam model of a composite precast structure is described in papers [5] and [6] (Fig. 2). The load bearing capacity of this model within the accidental situation is influenced by two systems of ties, which are (Fig. 2):

- ties connecting beams over their supports,
- ties connecting hollow core floors over supports perpendicular to the span of floor.

The reinforcement in the topping usually uniformly distributed over the full area of the diaphragm (welded fabric mesh) may be taken into account as effectively coating with above specified additional ties.

Contrary to the principles named as indirect design approach in case of APA the dimensions of all ties must be determined by calculation.

Studies by means of finite element method static and dynamic approach have been carried out by the authors and the results of those studies brought valuable data about the behaviour of a locally damaged framed structure.

2. DESCRIPTION OF MODEL AND ANALYSIS

2.1. Analysis of the object and main objectives

The skeleton structure consists of prestressed hollow core slabs SP320 simply supported by prestressed beams type RR 500/490 and precast columns.

Two internal spans with section through the beam and column assumed to be removed in accidental situation is shown in Fig. 2.

Main objectives of the analysis are to compare the simple two-beam model with FE results, in particular:

- calibration of the simplified (two-beam) calculation model according to bending stiffness EJ with particular focus on the following features:
  - $b_{eff.acc} > b_{eff}$
  - the properties of part ② are stable due to dominant compression whereas the properties of part ① are much influenced by the dominant tension state,
  - maximum displacements in tensile strength of the joints within the post elastic range are limited,
- search for capacity reserves, an example of such are the limitations along the horizontal plane particularly if the damaged part of the floor, is limited by undamaged floor portions,
- estimation of differences in the calculation model due to actually dynamic effects; this is a classical task for the everyday practice.

2.2. Structure in accidental situation

It is assumed that the accidental situation means that one internal column is removed and the secondary-load carrying structure is formed. That structure consists of a doubled-span of the beam in permanent situation assisted by the negative moment action over the supports.

<u>Two-beam approach</u>

The static analytical investigation based on the two-beam method (Fig. 3) was carried out by the authors. The method takes into account the influence of interaction (K_s) between slab ② and beam ① as well as the reduction of precast beam stiffness $(EJ)_1$* due to discontinuity in the joint over the removed column. Additional rotational stiffness (K_1) over supports due to span continuity is also taken into consideration.

To stabilize the secondary system the following items were necessary:

- full interaction between slab and tie beam (to provide enough effective flange width equal to 3.2 m),
- three bars #32 placed in tie beam in the middle and over the support of secondary system (Fig 2.),
- additional influence of the dowel action in joint between the head of removed column (remains in accidental situation) and precast beam. The main elements of those joints are two dowels embedded in column and the end of precast beam on each side of column head. Stirrups in column and u-bar loops in the beam enclose the dowels – see item 2.3.

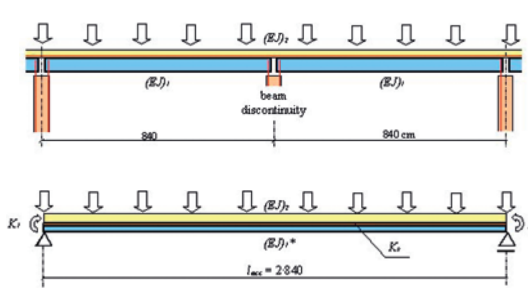


Figure 3.
Model used in the two-beam method a) real model, b) idealized model

FEM approach

FE analyses were carried out using the ABAQUS 6.6 software. Basing on the two beam method results, three numerical models dependent on reinforcement position and quantity were considered:

Model 1 reinforcement is placed in insitu tie beam, 3#32 bars are adopted. Full interaction between slabs and tie beam is assumed, the effective flange width was assumed to be 3.2 m. No additional column head influence is active.

Model 2 in addition to the previous point it is assumed that the joint between head of precast columns and beams (2#32 dowels – see Fig. 2a) remains in accidental situation. This model corresponds to the model used in the two-beam method

Model 3 the same situation as in item 2, but the 4#32 bars are adopted instead of 3#32.

Models consist of the following finite elements

- bilinear plane stress quadrilateral elements with reduced integration (CPS4R) for concrete members,
- 2-node linear 2-D truss elements (T2D2) for reinforcement in tie beam,
- 3-node quadratic beam in a plane (B22) for dowels,
- 4-node two-dimensional cohesive elements (COH2D4) for interface between tie beam and precast beam,
- connector (spring) elements for modelling tie beam reinforcements in joints and modelling the continuity of beam span,
- contact elements in joints.

Symmetric half of finite element model is shown in Fig. 4. The reinforcement in tie-beam and dowels are embedded in concrete members. The load is modelled by the self mass of the structure and some additional mass and vertical gravity acceleration. Static and dynamic (as a result of slow and instantaneous column removal) analyses for each model were carried out to check the capacity of the secondary system. Static analyses assume that the gravity load was increasing linearly in time to the secondary bearing system. The dynamic analysis consists of two steps. In the first step the gravity load applied to the structure in permanent situation (with internal, non-damaged column acting as a vertical support) was increasing linearly in 10 seconds (quasi-static approach), then the support simulating the column was instantly removed in the beginning of the second step. Dynamic analyses were based on central-difference operator. To reduce the computer cost, mass scaling was used in the first step.

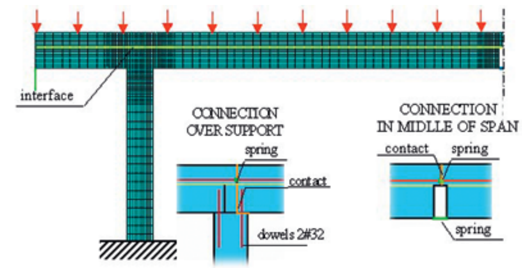


Figure 4.
Finite Element Model

2.3. Material modelling

General steel behaviour

Steel is assumed to behave as an elasto-perfectly plastic material in both tension and compression as shown in Fig. 5. No additional hardening due to strain rate is assumed. The mechanical properties correspond to the steel grade Bst500.

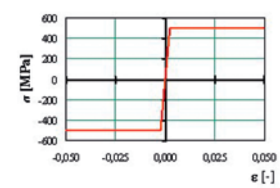


Figure 5.
Stress-strain diagram for steel

Reinforcement behaviour in tie beam in joints

In the joints in the centre of the span and over supports of the secondary system (Fig. 4) the reinforcement is provided as a spring with the following elastic stiffness and other properties as shown in Tab. 1:

$$K_{spring} = \frac{E_s A_s}{l_a} \qquad (1)$$

where l_a is the equivalent length of free elongation of bar in concrete equal $l_a = 30\phi$

Table 1.
Reinforcement properties in tie beam in joints

		Model 1&2 (3#32)	Model 3 (4#32)
elastic stiffness	K_{spring} [kN/m]	500000	667000
yield force	N_y [kN]	1200	1600
elongation at yield	δ_y [mm]	2.4	2.4

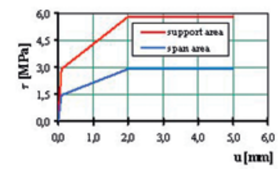
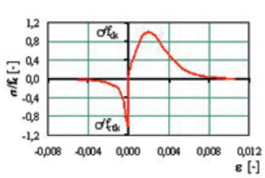


Figure 7.
Shear stress – displacement diagram for interface between precast beam and tie-beam

Concrete behaviour

Concrete elements are modelled as linear-elastic and nonlinear. For prestressed precast beams and columns linear elastic model is used except the head of column. Precast slabs and in-situ concrete is assumed to be nonlinear. For linear-elastic behaviour only Young's Modulus, Poisson's ratio equal 0.167. For nonlinear behavior of concrete the "Concrete Damaged Plasticity" model from Abaqus material library is assumed in analysis. Uniaxial stress-strain relationships are shown in Fig. 6. Two grades of concrete is used.



	insitu C30/37 (B37)	precast C50/60 (B60)
E_{cm}	30 Gpa	40.1 GPa
f_{ck}	30 Mpa	50 MPa
f_{ctk}	2.0 Mpa	2.9 MPa

Figure 6.
Stress-strain diagram for concrete – uniaxial compression and tension

Interface behavior

Interface acts between the precast beam and tie beam (Fig. 7). The stirrups are included in the interface behaviour. The trilinear equilibrium path for the interface is based on CEB-FIB Model Code. The interface is divided into two areas depending on the quantity of shear reinforcement:

- support area which corresponds to 2#10 @ 100 mm stirrups (2 m zone on the left and right side of the support),
- span area which corresponds to 2#10 @ 200 mm stirrups.

Interface is modelled using traction-separation law with relevant damage and damage evolution criteria.

Calibration of column head and precast beams joint (dowel action)

To calibrate the behaviour of joint between the head of column and beam (dowel action) the auxiliary 3D FE model was created. The model is symmetric, the plane of symmetry is cutting the head of the column in halves. Apart from that head of the column, the model consists of part of the beam, and two dowels embedded in concrete members, connecting column and beam. The stirrups in column and loops in precast beam also restrain the dowel action. The displacement to the precast beam was applied and the reaction in the plane of symmetry was recorded. The model and the equilibrium path for this joint are shown in Fig 8.

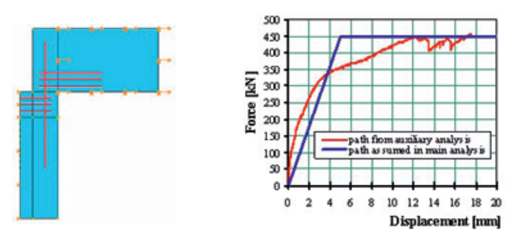


Figure 8.
Shear stress – displacement diagram for interface a) auxiliary model, b) results

Basing FE experiment the spring with following simple elasto – perfectly plastic properties was assumed defining the behavior of this joint in main models (Model 2 and 3):

Table 2.
Properties of column head – precast beam joint over removed column

Displacement at yielding	Yield force value	Stiffness in elastic range
0.005 m	450 kN	90000 kN/m

3. RESULTS

The results showing internal forces in joints (tension in reinforcement, and compression in concrete), relevant elongation of bars in joint and displacements in the state of equilibrium are shown in Fig. 9, Tables 3 and 4.

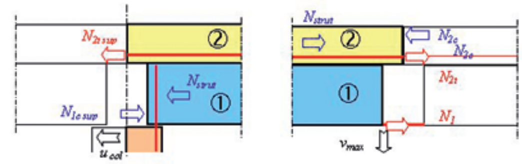


Figure 9.
Scheme of internal forces in joints a) over the support, b) in the middle (over removed column)

Table 3.
The values of internal forces based on the results of two-beam, static (S) and dynamic (D) FEM analyses

		N_1 [kN]	N_{2c} [kN]	N_{2t} [kN]	$N_{1c.sup}$ [kN]	$N_{2t.sup}$ [kN]	N_{strut} [kN]
Two beam [1)]		490	1840	1350	1420	1420	-
Model 1	S	-	1420	1200 [3)]	1420	1200 [3)]	220
	D [2)]						
Model 2	S	450 [3)]	1640	1010	1280	1100	180
	D [2)]						
Model 3	S	450 [3)]	1700	1080	1320	1150	170
	D	450 [3)]	2300	1600 [3)]	1850	1600 [3)]	250

[1)] elastic solution
[2)] no static equilibrium has been found
[3)] plastic yield has been reached

Table 4.
The values of elongations and displacements based on the results of static (S) and dynamic (D) analyses

		δ_{1t} [mm]	δ_{2t} [mm]	$\delta_{2t.sup}$ [mm]	u_{col} [mm]	v_{max} [mm]
Model 1	S	-	3.5 2)	3.8 2)	6.5	78
	D [1)]					
Model 2	S	8.0	2.0	2.2	3.8	50
	D [1)]					
Model 3	S	6.5	1.6	1.7	3.2	42
	D	52.0	11.0 2)	7.5 2)	12.0	280

[1)] no static equilibrium has been found
[2)] elongation at yield 2.4 mm has been exceeded

Symbols in table 4 have the following meanings:

- δ_{1t} – elongation of column-beam joint in the middle of the secondary resisting system,
- δ_{2t} – elongation of reinforcement in the middle joint of the secondary resisting system,
- $\delta_{2t.sup}$ – elongation of reinforcement at the joint over support of the secondary resisting system,
- u_{col} – horizontal displacement of the top of column,
- v_{max} – maximum vertical displacement of the secondary resisting system.

Comparison between the two-beam method and static FEM approach (Model 1S and Model 2S)

The following phenomena were observed:

- static analyses show that there's reserve in the secondary bearing system (Model 2S) comparing to analytical two-beam method. The forces in reinforcement in joints are smaller in FE analysis and stay within the elastic range.
- one of the reasons for smaller forces mentioned above is the additional strut action due to lateral column stiffness which is confirmed by the lateral displacement "in direction outside" of the column head. The other reason is the true column width in FE model reduces the clear span of beam.
- in case of lack of influence of the column head in

accidental situation, the FE analyses show, that the model is still able to obtain the state of equilibrium. The costs of that are quite high plastic elongations of reinforcement in all joints (plastic hinges) and as a result bigger vertical displacements and bigger strut forces due to lateral column stiffness. The plastic elongations obtained in all joints mean that this solution is not quite stable.

- the rest of column head plays quite significant role in obtaining equilibrium. Due to this additional interaction it was possible to stay with safe elastic elongations in the tie beam reinforcement.

<u>Comparison between two-dynamic and static FEM analysis</u>

Dynamic analysis shows much stronger response of the structure to this accidental event and particularly:

- it was not possible to obtain the static equilibrium with the quantity of reinforcement as in Models 1 and 2. Besides the influence of column head in the middle of additional bar in tie beam was provided.
- comparison of vertical displacements (Fig. 10) shows that the motion of secondary system was much more damped in case of Model 2 then Model 1, but not enough to stop the system as in Model 3. Possibly the quantity of reinforcement required to stabilize the system may be somewhere between Model 2 and 3.
- weakness of joint over support in compression (Fig 11) as a result of lower quality concrete infill between the precast beams is another phenomenon which disturbs obtaining equilibrium in dynamic analyses. This compression, is a superposition of bending and strut action mentioned above. In dynamic situation this compression zone is exposed to higher impact and consequently to bigger failure. The failure of this zone is reducing the strut action due to lateral stiffness of columns.
- the costs of the equilibrium in dynamic action are much higher than in static analyses. Elongations of all steel components needed to stop the secondary structure are several times larger, especially in the joint between the rest of column and precast beams in the middle. Also much bigger vertical displacement occurs.

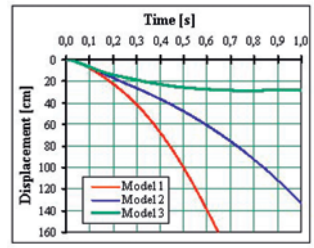


Figure 10.
Time history record of displacement in the centre of the secondary system after column removal for dynamic analysis

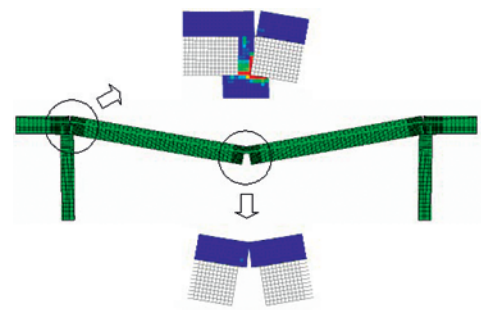


Figure 11.
Deformation of the structure and damage of concrete in compression in the state of equilibrium, scale 5:1

4. CONCLUSIONS

Basing on the above results some practical recommendations may be formulated, as well as the ways of further investigations.

- Two-beam model in the simplified analysis can be effectively used for the design of alternative bearing model in an accidental situation of a precast framed structure. The numerical approach presented here, in both static and dynamic versions, can be a good tool for further calibration of that model and that is a current task of the authors.
- Using the reserves within the proper level of safety:

  The results show in general two ways of stabilizing the structure: the elastic stabilization (static analysis) and post elastic stabilization (especially dynamic analysis).

  The level of safety of the first one is much higher because of difficult way of controlling the non-elastic behaviour of joints exposed to large plastic elongations. One of the possible best ways of designing is to reduce the post-elastic response of the structure and search for the reserves helping to stay close to elastic range. In current calculations two phenomena acted as additional interactions stabilizing the secondary bearing system:

  – the influence of joint between column head and precast beam transferring tensile forces in the middle of the structure,

– the strut action as an effect of lateral stiffness of column causing additional compression in span.

The other possible items which may be considered as reserves are:

– structural topping (with embedded reinforcement mesh) increasing the stiffness and bending capacity especially in support joints,

– suspension effect of floor in direction perpendicular to the main beam,

– in plane compression action due to lateral stiffness of the floor.

- Proper design of the column-precast beams joint in tension and compression:

  The results shows that the influence of the remaining column head play a significant role in stabilizing the secondary structure, especially in dynamic situation in which there is danger of very large elongations. To increase the effectiveness of this joint some additional solutions like grouting the dowels between column and beam and adding confining loops in precast beam and stirrups in column around the dowels should be provided.. It is also important to fill the spaces between beams with concrete which helps to distribute the compression over the support in accidental situation.

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