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Alternative Bridging Systems in Precast Concrete Structures

Systèmes porteurs alternatifs dans les structures préfabriquées en béton armé

Alternative überbrückende Systeme in Gebäuden aus Stahlbeton-Fertigteilen

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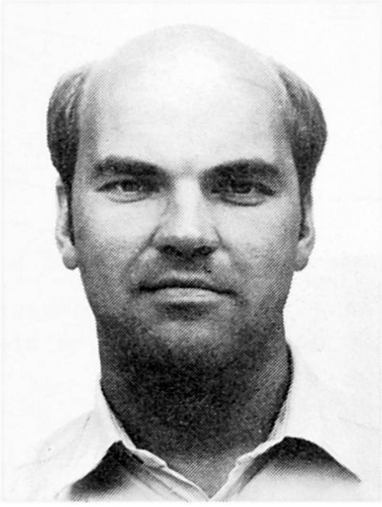

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SUMMARY
Building structures should be designed to prevent progressive collapse. Primary damage of the structural system can be accepted as long as the overall stability remains and an alternative load-bearing system bridges over the damaged area. An approach for the design and analysis of alternative bridging systems in precast structures is exemplified by means of rotation mechanisms. It is shown how the non-linear behaviour of tie connections affects the dynamic resistance.

RÉSUMÉ
Il faut construire les structures des bâtiments en vue d'éviter un rupture progressive. Un dégât primaire du système structural peut êtere accepté si la stabilité générale est garantie et si un système porteur alternatif peut remplacer la partie détruite. Une méthode pour la construction et l'analyse des systèmes porteurs alternatifs dans les structures du béton armé est illustrée par des mécanismes rotatifs. On montre comment la résistance dynamique est influencée par le comportement non-linéaire des assemblages.

ZUSAMMENFASSUNG
Gebäude müssen so dimensioniert werden, dass ein fortschreitender Zusammenbruch verhindert wird. Primäre Schäden am Tragsystem können akzeptiert werden solange die Gesamtstabilität erhalten bleibt und ein alternatives lasttragendes System den Schaden überbrückt. Eine Methode der Dimensionierung und Analyse von alternativen überbrückenden Systemen in Gebäuden aus Stahlbeton-Fertigteilen ist mit Hilfe von Rotationsmechanismen erklärt. Damit kann gezeigt werden, wie die nichtlineare Wirkungsweise der Zugverbindungen die dynamische Tragfähigkeit beeinflusst.

1. INTRODUCTION

For a certain presupposed local damage in a precast structure, possible collapse mechanisms and the corresponding alternative bridging systems will be determined by the actual joint locations and detailing. The deformations which follow the primary failure may be concentrated to the joints. Accordingly, the resistance of the bridging system will mainly depend on the behaviour of the structural connections which are strained during the transition, for instance tie connections across joints which open up, see Fig. 1.

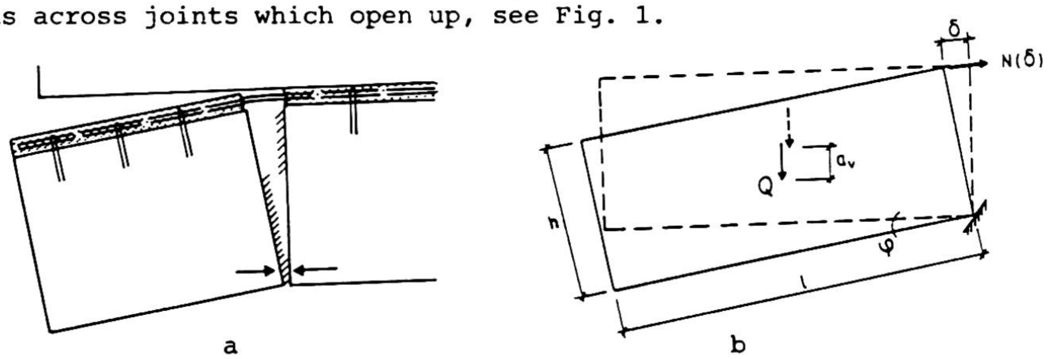


Fig. 1 A wall panel forming an alternative load-bearing system by cantilever action at large plastic deformations of a tie connection
a) example of detailing
b) model for the collapse mechanism

In this paper an approach for the design and analysis of alternative load-bearing systems in precast concrete structures is presented. The aim is to show how the non-linear behaviour of tie connections will affect the dynamic resistance of alternative load-bearing systems. The presentation is limited to systems which can be characterized as rotation mechanisms, as in Figs. 1 and 3. The resistance of the system should be determined by the tensile action of tie connections only. The imposed elongations of the tie connections should be caused by the rotation of the system around one well-defined axis.

It is important to design and detail elements, connections, anchorages etc. in consequence with the intended collapse mechanism. By that means the behaviour can be controlled to a considerable extent. Anchorage failures and brittle ruptures of other components than the ductile ones should be prevented by a proper design and detailing.

When the system is composed from interacting structural elements, as in Fig. 3, the connections between the elements must have sufficient strength and rigidity to keep the integrity of the system.

The design approach, as it is presented, is not applicable on collapse mechanisms including joint slips or suspension action, as in catenary systems. However, the method can be extended to cover also those cases if the design formulas are expressed in accordance. The design of catenary systems with the proposed method is exemplified in [2].

2. NON-LINEAR BEHAVIOUR OF TIE CONNECTIONS

The basic behaviour of different types of tie connections between concrete elements has been examined in previous investigations at Chalmers University of Technology [1]. It was then of special interest to study the connections at large imposed deformations resulting in a non-linear behaviour. The test methods and test results are presented in [1] together with proposed formulas which can be used for estimation of the ultimate deformation capacity of tie connections.

It was concluded that the behaviour of simple tie connections could be characterized by schematic bilinear relationships between the tensile force N and the elongations δ, as exemplified in Fig. 2a. The relationships are valid for tie connections where the fractural load of the tie bar is wholly anchored by bond or by end-anchors.

The area which is bounded by the tensile force graph in the load-displacement relationships represents the strain energy W_{int}. The efficiency of tie connections under imposed elongations will depend on the strain energy development. The efficiency for a certain elongation δ can be expressed by a dimensionless parameter $\xi(\delta)$.

$$\xi(\delta) = \frac{W_{int}(\delta)}{N_{max} \cdot \delta} \tag{1}$$

where N_{max} = fractural load of the tie bar.

For the schematic load-displacement relationships presented in Fig. 2a, the corresponding efficiency functions are illustrated in Fig. 2b.

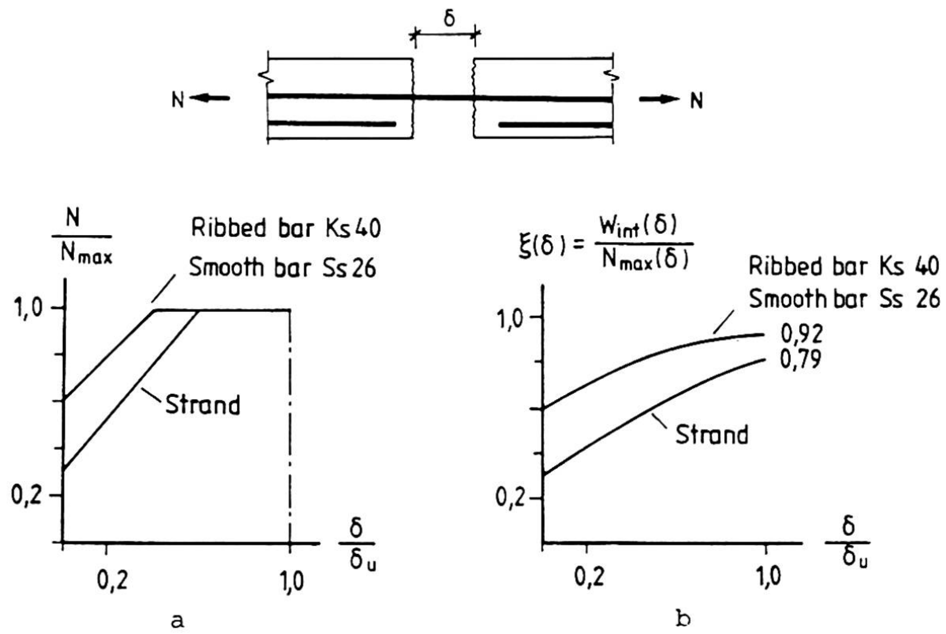


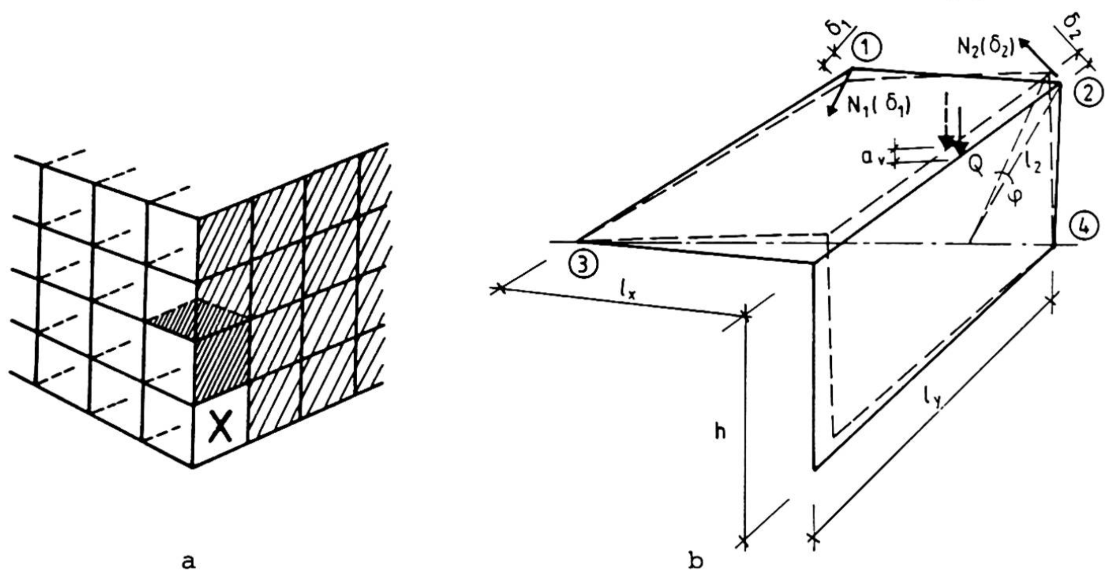
Fig. 2 Characteristic relationships for simple tie connections provided with wholly anchored tie bars from smooth bars (Ss26) or strands anchored by end-anchors or ribbed bars (Ks40) anchored by bond*
a) relationship between tensile force N and elongation δ
b) efficiency function

* The tie bars were made from ordinary reinforcement bars of type Ks40 or Ss26 according to Swedish Standards. Type Ks40 stands for a high bond, ribbed, hot-rolled bar with a minimum yield stress of 390 MPa. Type Ss26 stands for a smooth, hot-rolled bar of mild steel with a minimum yield stress of 260 MPa.

3. ANALYSIS OF ROTATION MECHANISMS

Consider a precast building with a partial damage of the structural system. A system of interacting precast elements forms a composed cantilever above the damaged area. A driving force Q is acting in the centre of gravity of the cantilevering system. The driving force is constituted by gravity forces, i.e. the weight of the elements and working loads.

Under the action of the driving force, the cantilevering system tends to rotate but the rotation is counteracted by tie connections when they are forced to elongate. Such a cantilever system is exemplified in Fig. 3. Full-scale tests on this type of alternative load-bearing systems were reported in [3].



a b

Fig. 3 Example of an alternative load-bearing system acting as a composed cantilever above the damaged area
a) assumed partial damage in a stabilizing gable wall
b) model for the alternative load-bearing system. Two interacting tie connections 1 and 2. Rotation axis 3-4

In the design approach, the elements are now assumed to be perfectly rigid. Hence, there will be a simple geometric relationship between the vertical displacement a_v of the driving force and the elongations δ_i of each tie connection i. For small rotations the following approximative expression can be adopted

$$\delta_i \cong \frac{l_i}{l_{q0}} a_v \qquad (2)$$

where l_i = radial distance between the rotation axis and tie connection i
l_{q0} = horizontal distance between the rotation axis and the driving force Q in the undeflected state

The bridging effect of the alternative load-bearing system can be regarded as a resistance $R(a_v)$, defined as the ability to withstand a driving force acting in the centre of gravity. For a certain rotation of the cantilever system and a corresponding vertical displacement a_v of the driving force, the static resistance will be

$$R_{stat}(a_v) = \frac{1}{l_q} \Sigma N_i(\delta_i) \cdot l_i \qquad (2)$$

where l_q = actual horizontal distance between the rotation axis and the driving force Q
δ_i is determined by (2)

For estimation of the dynamic resistance it is now favourable to introduce a formal value R_{max} of the maximum static resistance in the undeflected state

$$R_{max} = \frac{1}{l_{q0}} \Sigma N_{i,max} \cdot l_i = \Sigma R_{max,i} \qquad (3)$$

where $R_{max,i}$ = contribution to R_{max} from tie connection i

This value is formal as the tie connections are contributing with maximum capacities simultaneously and without any displacement of the cantilever system. In the real situation the tie connections may fracture one after the other depending on the locations and the mutually deformability.

The dynamic resistance must be related to a certain state of displacement. Hence, the designer has to choose a maximum displacement $a_{v,max}$, for which the deflected state of equilibrium should be obtained. The value of $a_{v,max}$, must be established with due regard to free space for displacements, elongation capacities of the respective tie connections and a desired safety level. The dynamic resistance $R_{dyn}(a_{v,max})$ states the maximum driving force Q_{dyn} which can be bridged in case of a sudden support removal, if the maximum displacement should be limited to $a_{v,max}$.

In order to analyse the dynamic effects during the deflection course, the collapse mechanism is regarded as an one-degree-freedom system. On the safe side the support is assumed to be lost suddenly. The system is exposed to the driving force Q, which acts with constant intensity during the deflection course. The motion of the rotating element is counteracted by the action of the tie connections. This action varies during the deflection course, and the composed effect of the interacting tie connections is represented by the resistance $R(a_v)$ according to (2).

A deflected state of equilibrium can only be possible if the velocity of the rotating system equals zero. This is the case when the internal energy of the system equals the external energy during the deflection course, i.e.

$$W_{int} = W_{ext} \tag{4}$$

The internal energy which is related to a certain displacement a_v of the driving force will be constituted by the strain energy of the tie connections under the corresponding imposed elongations δ_i. The external energy can be expressed as the driving force times its vertical displacement. By means of (1) the condition of energy equilibrium (4) can now be expressed as

$$Q_{dyn} \cdot a_{v,max} = \Sigma\ \xi(\delta_{i,max}) N_{i,max} \cdot \delta_{i,max} \tag{5}$$

where $\delta_{i,max}$ is determined by (2) for $a_v = a_{v,max}$.

By introducing the geometrical relationship (2), the dynamic resistance $R_{dyn}(a_{v,max})$ can be derived from (5)

$$R_{dyn}(a_{v,max}) = \Sigma\ \xi(\delta_{i,max}) \frac{l_i}{l_{q0}} N_{i,max} \tag{6}$$

or by means of (3)

$$R_{dyn}(a_{v,max}) = \Sigma\ \xi(\delta_{i,max}) R_{max,i} \tag{7}$$

Hence, the dynamic resistance can be regarded as a reduced value of the maximum static resistance according to (7), where the contributions from the respective tie connections have been reduced by efficiency factors $\xi(\delta_{i,max})$. The efficiency $\xi(\delta)$ will always, according to the definition (1), be less than or equal to 1. The actual value depends on to what extent the elongation capacity $\delta_{i,u}$ of the respective tie connections is utilized.

In addition to (7) the following condition of static equilibrium must be fulfilled in the deflected state. Otherwise, the system is under acceleration and will continue to deflect.

$$R_{stat}(a_{v,max}) \geq Q_{dyn} \tag{8}$$

where $R_{stat}(a_{v,max})$ is determined by (2).

The formulas (7) and (8) are appropriate to use in the design of alternative load-bearing systems. Examples of application are presented in [2] and [4].

4. COMPARISON WITH TEST RESULTS

In order to check the applicability of the theoretical approach a series of tests concerning a simple well-defined collapse mechanism was carried out [5]. The test specimens were formed by strips of precast hollow core floors on three supports, see Fig. 4. A collapse situation was simulated by a sudden removal of an exterior support. Thus, one panel was transformed to a cantilever and the adjacent tie connection was loaded in negative bending. Normally, the yield strength was reached in the connection, resulting in large plastic rotations.

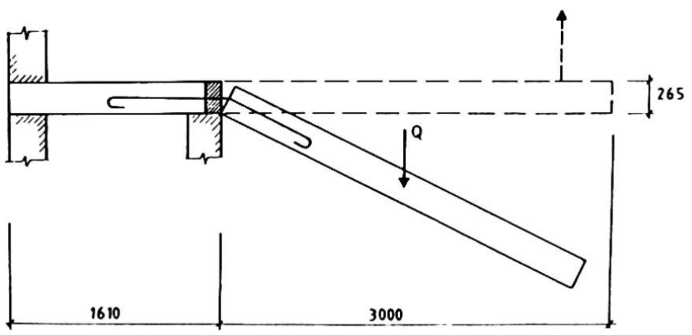


Fig. 4 Test arrangement

In most of the tests it was possible to take advantage of the ductility of the tie connection and receive a deflected state of equilibrium. The theoretical analysis was made in accordance with the principles presented above. The calculated values of the dynamic resistance were always in good agreement with the actual driving forces.

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