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Design and Detailing of Cellular Concrete Structures

Conception et détails des structures cellulaires en béton

Entwurf und Ausführung von Beton-Zellenkonstruktionen

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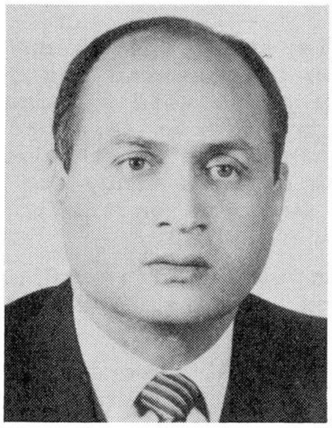

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SUMMARY

An experimental-theoretical study was conducted to investigate the general deformational behaviour of reinforced concrete cellular structures. Six reinforced concrete voided slabs, and six reinforced concrete box section girders were tested. The varying parameters of the voided slabs were the void's diameters and the percentage of reinforcement, while for the box section girders, the varying parameters were the percentage of reinforcement and the end conditions, (warping restrained or unrestrained). The finite element method was used in the analysis of these cellular structures. General conclusions are summarized.

RÉSUMÉ

Une étude expérimentale ainsi que théorique a été conduite afin d'examiner le processus de déformation des structures cellulaires en béton armé. Six dalles et six caissons ont été testés, en tenant compte des paramètres suivants: diamètre des vides et pourcentage d'armature pour les dalles, pourcentage d'armature et conditions aux limites (torsion libre ou empêchée) pour les caissons. La méthode des éléments finis a été utilisée dans l'analyse de ces structures cellulaires. Les conclusions sont résumées.

ZUSAMMENFASSUNG

Eine experimentelle und theoretische Studie wurde durchgeführt, um die allgemeine Verhaltensweise von Stahlbeton-Zellenkonstruktionen zu ermitteln. Sechs Stahlbeton-Hohlplatten mit verschiedenen kreisförmigen Aussparungen oder unterschiedlicher Bewehrung und sechs Stahlbeton-Kastenträger mit unterschiedlicher Bewehrung und verschiedenem Endzustand (Krümmung, eingespannt oder nicht eingespannt) wurden getestet. Die Methode der Finite Elemente wurde benutzt, um diese Strukturen zu analysieren. Die allgemeinen Schlussfolgerungen sind zusammengefasst.

1. INTRODUCTION

Reinforced concrete is particularly well suited for use in bridges, because of its durability , rigidity and economy, as well as the comparative ease, with which a pleasing appearance can be achieved. In the recent years, there has been a general tendency to adopt cellular construction for reiforced concrete small & medium-span bridges. This has been a result of functional structural and aesthetic requirements coupled with economic considerations.

In the present work an experimental and theoretical study was conducted to define and explain the general deformational behaviour of reinforced concrete cellular structures under symmetrical and unsymmetrical cases of loading within the serviceability and uultimate states and up to the failure of this type of structures.

The specified aims of this study was to define a simplified method for the design of R.C. voided slab bridges and box girders. Also, this study aims to study the effect of changing the void's diameter, the location and percentage of the longitudinal and transverse reinforcement on the characteristics of load distribution betweenthe webs of the voided slsbs from zero up to the failure load. Also the aim of this study was to investigate the effect of the warping restraint at the supports on the torsional and warping behaviour of R.C. box girder bridges.

The finite element method was used in this study for the analysis of the voided slabs, and the box girders. The adaptability and validity of this method is discussed.

The results of this experimental-theoretical study were combined with other available information and the code provisions to formulate some recommendations to simplify the analysis, design and detailing of this type of structures.

2. ANALYSIS

In the analysis and design of voided slabs or box girders, the commonly used approach is to assume the concrete to be uncracked and linearly elastic, and thus ignoring the reinforcement. This approach has the advantage of simplicity and closely modeling the bahaviour of the structure within the service load level. However, this approach lags accuracy, and may lead to unnecessary overestimating the dimensions of these structures. In addition, it cannot predict the nonlinear behaviour of the reinforced concrete cellular structure up to failure.

2.1 Finite Element Analysis

2.1.1 Element used

In this study a layered rectangular element was used with 7 degrees of freedom per node for the voided slabs, and 6 degrees of freedom per node for the box girder.

The rigidity matrix of the rectangular element was developed using the concept of layered plates, (i.e. the integration involving the material properties is being done layer by layer [7,12]). The structures were divided into a number of layers of different elastic properties as follows;

- i- The voids were replaced with an orthotropic solid core layer of equivalent properties as the actual voids.
- ii- The steel reinforcement was replaced with a smeared orthotropic layer which resists only normal stresses, and Poisson's ratio is considered to be equal to zero.
- iii- The solid concrete layers were considered as isotropic solid layers in the elastic stage, and orthotropic in the inelastic stages.

2.1.2 Material Nonlinearity

The analytical model for concrete which was used in the present analysis was originally developed by Darwin and Pecknold [4]. In Darwin's model, concrete was assumed to be an orthotropic material in the two principal stress directions. In this model the concrete was treated as an incrementally linear elastic material. At the end of each increment, (or iteration), material stiffness were crrected to reflect the latest changes in deflection and strain. Also in this study the smeared cracking model was adopted in the solution(1,7). The advantages of this model was that it offers an automatic generation of cracks without the redefinition of the finite element topology,and second, it offers a complete generality in possible crack direction. The failure criteria used in this model was that proposed by Kupfer and Gerstle (8).

The steel is considred as an approximately elastic plastic material with yield stresses fy and elastic modulus Es. After the yielding of the steel its tangent modulus of elasticity was reduced. It was further assumed that the reinforcement carry only axial stresses in its direction, hence, the principal stress directions was always taken in the global x-y directions, the same as the reinforcement arrangement. Perfect bond was assumed between the steel and concrete layers.

Finally the nonlinear finite element analysis was performed in an incremental manner using an iterative scheme within each load increment. The Newton-Raphson, or the modified Newton-Raphson scheme were used for stiffness updating.

3. EXPERIMENTAL WORK

3.1 The voided slabs

Six reinforced concrete voided slabs with 10 voids were tested. The dimensions of these slabs are 1.04 x 1.80 m. and thickness 12 cm. These slabs were tested, as simply supported on spsn of 1..60 m., twice. Once with a single concentrated load acting at center of gravity of the slab within the elastic range, and the second time, with an eccentric concentrated load, of eccentricity 0.3 m. from the center of the mid section. The six slabs were divided into two groups, each group consisted of three slabs as follows;

Group (1) : The three slabs had a bottom reinforcement of 10 ϕ 6 mm/m' in the longitudinal direction and 10 ϕ 6 mm/1.5 m' in the transverse direction. The varying parameter was the void's size (For slab S1/6 the void diameter was 63 mm., slab S2/6 the void diameter was 50 mm. and for slab S3/6 the void diameter was 40 mm). The spacing of center line of voids was 0.1 m.

Group (2) : The three slabs had the same void sizes as used in group (1) but the reinforcement used was ϕ 8 mm instead of ϕ 6 mm. The slabs were named S1/8, S2/8 and S3/8, respectively.

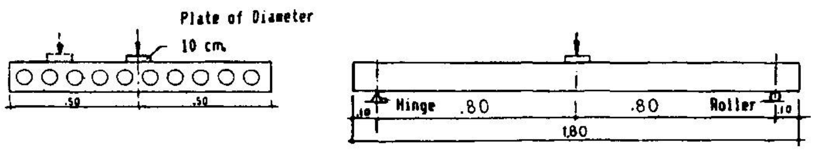

Fig. 1 Test setup for the voided slabs

3.2 The box girders

Six Medium size direct model of R.C.box section girders were tested. The six models had the same length, (2.30 m), and cross-sectional dimensions, (the outer and inner dimensions were 400x260 mm and 260x120 mm. respectively), but they had a different end conditions, (warping restrained or unrestrained).

Also, they had a different percent of reinforcement in both the longitudinal and the transverse directions. These girders were divided into the following two groups;
Group (3) : [G1,G2,G3], consisted of three models which had no transverse diaphragms at the supports, (warping unrestrained condition). Within this group, three girders had a different percent of reinforcement in both the longitudinal and transverse directions.
Group (4) : [G4,G5,G6], consisted of three models which had two end diaphragms of length 400 mm. at both ends to simulate the warping restraint condition at the supports. Also within this group, these girders had a different percent of reinforcement in both directions similar to those of group (3).
All these girders were tested on a fixed end condition of clear span 1.50 m. and were loaded with an eccentric cocentrated load at the midspan section to provide a combined torsion, bending and shear condition.

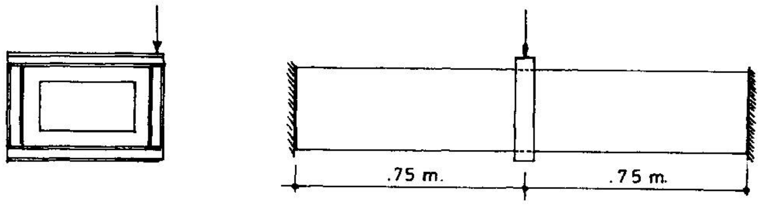

Fig. 2 Test setup for the box girders

4. BEHAVIOUR OF THE TESTED SPECIMENS

4.1 The voided slabs

The behaviour of the tested slabs can be summarized in the following points;

i) The first crack appeared at a load level of about one quarter of the ultimate load for all slabs.
ii) Increasing the transverse reinforcement, or decreasing the void depth ratio, leads to a more uniform load distribution between the webs of the voided slabs. This was observed by;
   a) Increase in the cracking load.
   b) Decrease in deflections and longitudinal strains of the loaded web and an increase in the transverse strains.
iii) Cracking due to longitudinal moments leads to a more uniform load distribution between the webs. This is due to the decrease in the longitudinal flexural stiffness of the slabs while the transverse flexural and torsional were approximately constant.
iv) As the void depth ratio increases, the ratio between the transverse and the longitudinal increases, while the ratio between the transverse and the longitudinal moment decrease. This was explained by the existence of shear deformations due to the cell distortions.
v) The effect of the torsional moment was obvious on the crack pattern of the slabs. This can be observed from the direction of cracking on the opposite sides of the slabs.

4.2 The box girders

The behaviour of the tested box girders can be summarized in the following points;

i) The end diaphragms had a slight effect on the cracking load but it increases the failure load.
ii) The end diaphragms reduce the vertical and lateral deformations of the loaded and unloaded webs.
iii) The longitudinal and transverse steel stresses at both the midspan and

support sections of the unrestrained condition were higher than those of the warping restraint condition at the supports. however, the box girders of group (3) reached the yield earlier than those of group (4).

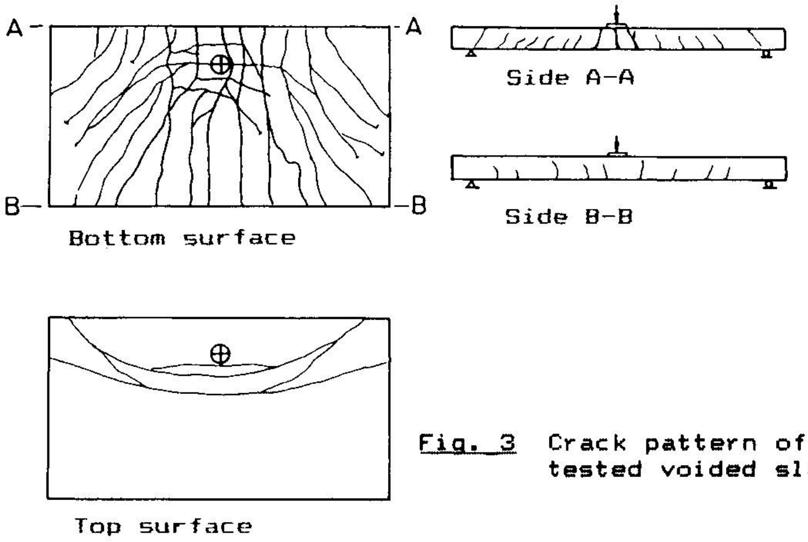

Fig. 3 Crack pattern of the tested voided slabs.

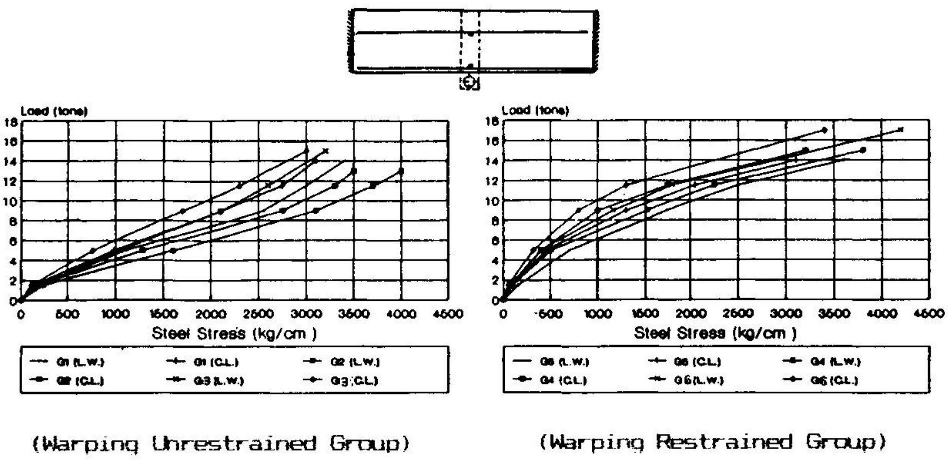

Fig. 4 Load-Longitudinal steel stress in bottom slab of midspan section for all box girders.

5. CONCLUSIONS

1) The proposed finite element model, which considers the nonlinear behaviour of concrete and steel, is a powerful tool in the analysis of reinforced concrete cellular structures, especially after cracking of concrete.
2) The transverse stresses should be taken into consideration, and hence care should be given for the detailing of the transverse reinforcement of this type of structures.
3) Shear deformations have a significant effect on the behaviour of cellular structures and its effect should not be neglected, and hence, special web reinforcement, and detailing should be considered.
4) The values of the transverse moments should be calculated individually taking into cosideration the ratio between the longitudinal and transverse reinforcement, and shoud not be related to the longitudinal moment by Poisson's Ratio.
5) The effect of torsional and the effect of warping restraint should be considered in the analysis and design of box girders structures and accordingly the detailing of the longitudinal and trasverse reinforcement at the support region is very important.

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