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REINFORCEMENT DESIGN FOR THE COMBINED EFFECT OF RESTRAINED SHRINKAGE AND APPLIED LOADS IN SLABS: A DESIGN CHALLENGE

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Abstract

The quantification of the necessary reinforcement for crack width control in highly restrained RC slabs still remains a subject of discussion in both scientific and practitioner communities, particularly when the simultaneous effects of applied loads and restrained shrinkage deformations are considered. Indeed, different authors/designers follow distinct approaches to deal with the problem. This is however a very important matter, because in slabs, the quantity of reinforcement is frequently determined by Service Limit States (SLS) of cracking. Therefore, the use of different design criteria for SLS can bring different performance levels, and also different global costs (e.g. reinforcement can be overdesigned, or under designed and then repairs may be in order).

In such context, this paper presents and analyses the results of a design challenge launched by the research teams at UMinho and UPorto to a set of design offices. The design challenge consists in the sizing of the necessary reinforcement to satisfy adequate cracking performance in a highly restrained slab. All information about geometry, materials, loads and boundary conditions are provided in the design challenge sheet provided to participants.

A total of 7 teams have provided answers to this design challenge. Results are treated anonymously in regard to participating teams. A discussion is held with basis on common and differentiating points, and finally an analysis of the authors using non-linear finite element analysis is made, targeting to better assist interpretation of the expectable behaviour of reinforcement solutions.

Keywords: concrete cracking; imposed deformations; applied loads; design challenge

1. INTRODUCTION

In view of the open discussion, in the scientific and practitioner communities, about design procedures for quantification of the required reinforcement for crack control in restrained structures subjected to imposed deformations and external loading, a research project was recently initiated. The project is entitled "*IntegraCrete* - A comprehensive multiphysics and multiscale approach to the combined effects of applied loads and thermal/shrinkage deformations in reinforced concrete structures". One of its first tasks consists in a design challenge, launched to design offices, to access the different practices used to design such reinforcement.

This paper describes the design challenge, summarizes the responses provided by the participants, and discusses the responses through the comparison with the results of nonlinear finite element analyses (NLFEA).

2. THE DESIGN CHALLENGE

2.1 General aspects about invitation and participation

The design challenge was sent by e-mail to a number of national (Portugal) and international design offices, with a formal letter of invitation, explaining about the nature of the research project. This type of challenge is not usual in engineering practice, and for such reason, a significant part of the invitation letter is reproduced below (introduction of IntegraCrete omitted, as well as contact information for submission of responses), providing self-explanatory grounds for the relationship established with the potential participants:

> *"…We are therefore inviting some known researchers and practitioners to participate in a design challenge for a highly restrained slab, as shown in the attached file "Design challenge V1.pdf". We invite you to participate in this design challenge by responding to it and provide your best estimate of reinforcement with some background reasoning. You may just make some hand calculations and scan them, if that is the most convenient form for you. The result should be sent within 3 weeks to miguel.azenha@civil.uminho.pt, please.*
> *We want to assess the dispersion of estimates on behalf of different designers/researchers due to the absence of established standards/guidelines for this purpose. Anyway, we will not disclose the identity of any of the participants.*
> *We will prepare a report of the project that we will share with all participants and even add you as a co-author in case you wish to do so and participate actively in the discussions. Please let us know about your interest in this specific concern."*

It is noted that the design challenge did not involve any kind of funding for the participants, and hence, all work would indeed be fully voluntary. For that reason, engaging a very wide number of responses was difficult by default. Anyhow, a total of 7 participants from industry could be mobilized up to completion of the challenge. It is however noted, that deadlines needed to be extended up to more than 3 months, to make sure that all voluntary participants could afford the necessary time for this matter.

The participants were A400 (http://www.a400.pt/), AdF (http://www.adfconsultores.com/), CENOR TPF (www.tpf.pt), KPH Leipzig (http://www.khp-leipzig.de/), Mott McDonald (https://www.mottmac.com/), Newton (www.newton.pt) and Streng (www.streng.pt). A note is given to the anonymous character or responses to this challenge: responses are labelled as #1 to #7, not corresponding to the order shown above: this was not about comparing performance and finding the best answer; it was rather targeted to evaluate potential differences and common points in the adopted approaches.

2.2 The design challenge posed to participants

As mentioned above, the design challenge was proposed to participants in an attached file named "*Design challenge V1.pdf*". It was devised as to be simple from the structural layout/supports point of view, with clear hierarchy of supports, having solid slabs and supporting beams and columns. So, the challenge included a one-directional solid slab of 15cm thickness (see Fig. 1), with 5m span, supported by transverse beams (0.3m x 0.5m), which in turn also have 5m span and are supported by columns (0.3m x 0.3m). The structure is composed of 10 spans of the slab, in a total of 50m and it is longitudinally restrained by two massive extremity blocks of concrete with 5m x 5m x 3m.

The exact information provided to the participants in the design challenge is reproduced below, with particular emphasis for the existence of two levels in the design challenge is shown in the text quoted below.

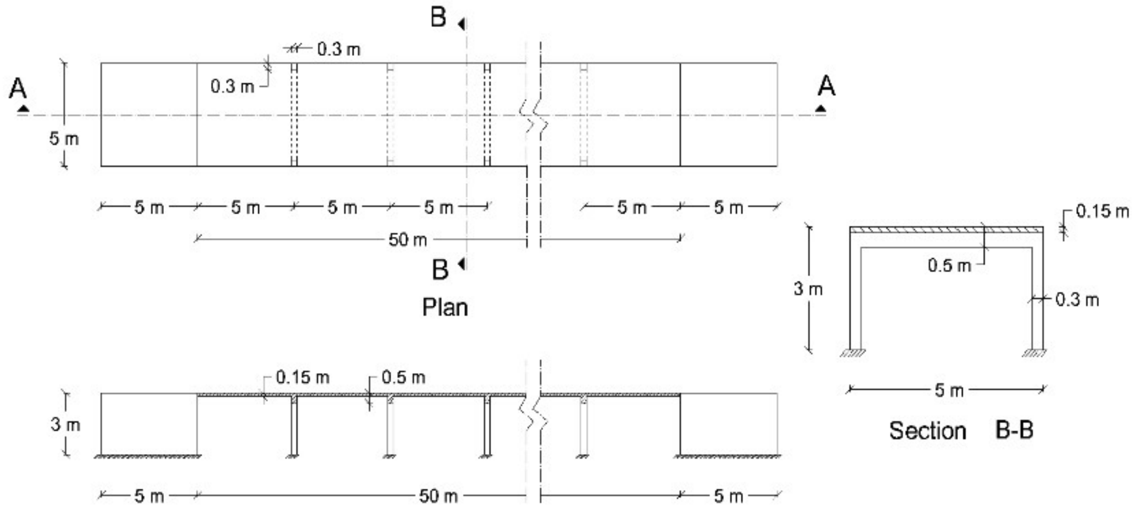


Figure 1: Relevant geometrical information for the design challenge

"Consider a restrained reinforced concrete slab, represented schematically in the figure, under the following conditions:
- *Concrete class C20/25; Steel class S400C; Concrete cover 30mm*
- *Environment: constant temperature T=20ºC and constant humidity RH=50%*
- *Slab is 15cm deep, with plan dimensions of 5m × 50m*
- *Slab is supported in 30 × 50cm beams of the same type of concrete/steel*
- *The beams are supported at their extremities by 30 × 30cm columns (3m tall), which are in turn rigidly fixed at their base.*
- *Disregard autogenous shrinkage and consider that drying and loading both start at t=28 days.*
- *At the extremities, the slab is rigidly connected to two massive concrete elements of 5×5×3m. Assume that the massive elements are hardened concrete with more than 1 year old, in thermal equilibrium with the surrounding environment. The massive elements are rigidly connected to an infinitely stiff foundation.*

• *Apart from self-weight, the slab has additional permanent loads g_k=2 kN/m^2 and a live load q_k=2kN/m^2 (ψ_2=0.3) - Residential building - Category A according to EC1.*

Design challenges:
1) Quantify the reinforcement necessary for an adequate control of crack widths (w_k<0.3mm) due to restrained shrinkage/temperature. In this part of the challenge, ignore the existence of applied loads and therefore disregard any bending reinforcement in the slab.
2) Considering the combined effect of applied loads and restrained shrinkage/temperature, quantify the necessary reinforcement and present the corresponding construction drawings for the slab."

3. RESPONSES TO THE DESIGN CHALLENGE

The responses are summarized by showing the reinforcement areas provided by each participant, for the two critical positions: the top surface, at the cross section over the support beam; the bottom surface, at the cross section through the mid-span, as shown in Figure 2. The structure under analysis exhibits, essentially, a unidirectional behaviour. Therefore, the discussion focuses on the longitudinal reinforcement only.

3.1 Challenge 1

All the participants adopted equal reinforcement areas at the top and bottom surfaces. This was expected in advance, because of the absence of bending moments. The results of each participant are shown in Fig. 3a. Group #5 did not provide an answer to Challenge 1. To a great extent, the responses to this first design challenge were mostly based on the equilibrium of forces at pre and post-cracking stages, as reported in equation 7.1 of EN1992-1-1:2004 [1], but with different strategies for assessment of the reduction factor associated to restraint loss due to cracking and other phenomena such as self-balanced stresses and viscoelastic effects. A significant number of participants have used the reduction factor approach devised by Luis [2]. Crack width calculations were vastly made with basis on expression 7.9 of EN1992-1-1:2004. In spite of the differences in approach, most participants reached a similar result, with an average of 5.2 cm2/m. For more details on design assumptions and results, see [3].

3.2 Challenge 2

The reinforcement calculated by each participant is shown in Fig. 2b. The methodologies applied by participants were once mostly focused on the combination of bending behaviour with the tensile force installed in the slab due to restrained shrinkage (composite bending), with the tension force being quantified with similar approaches to those exhibited in challenge 1. Then the stresses in rebars were calculated for cracked cross-sections with direct consideration of the composite bending, and then equation 7.9 of EN1992-1-1:2004 [1]. Differences arose mostly on the method to compute the reduction factor mentioned for challenge 1, and for the consideration of shrinkage in the crack width calculation expression.

It is noteworthy to mention the particular cases of Group 4, which consistently used a deformation compatibility approach devised by Dirk *et al* [4], and Group 5, which focused on the application of the recommendations of CIRIA C660 [5].

Group #1 adopted non-uniform reinforcement for the top surface at the cross section over the support beam: ϕ12//10 cm in a 1 m wide lateral band; and ϕ12//10 cm in the remaining central band. This option is motivated by the concentration of higher bending moments close to the lateral columns visible in Fig. 1. The value shown in Fig. 3 for this Group #1 is the area of reinforcement in the lateral band. All of the remaining participants assumed uniform reinforcement throughout the slab width. For the cross section through the mid-span, all the participants presented uniform constant bottom reinforcement over the slab width. Fig. 2b shows large differences in the area of reinforcement provided by the various participants, specially for the top surface.

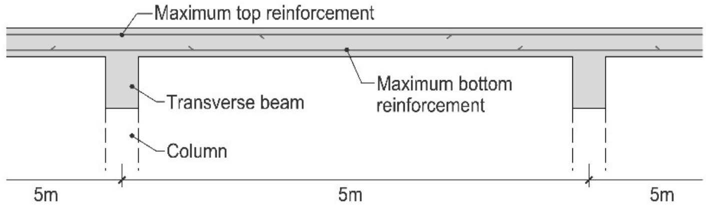


Figure 2: Critical positions for comparison of reinforcement areas provided by different teams

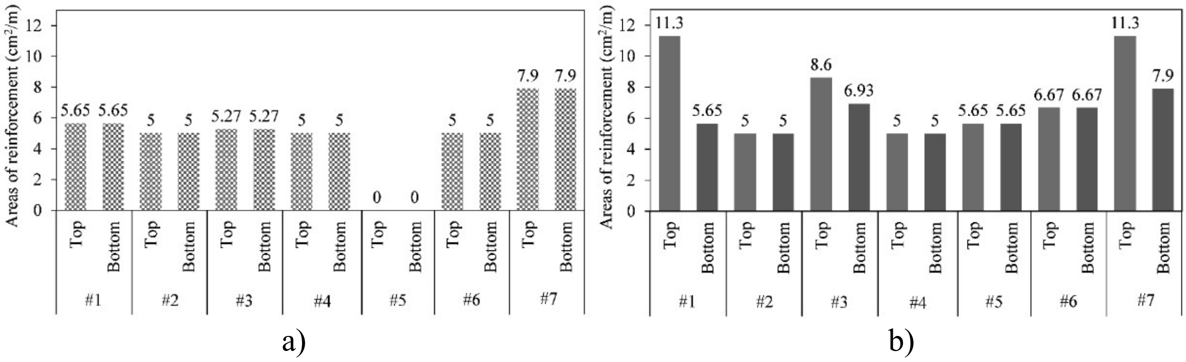


Figure 3: a) Top and bottom reinforcement areas for Challenge 1 b) Top and bottom reinforcement areas for Challenge 2

4. EVALUATING THE DESING CHALLENGE WITH NLFEA

The use of nonlinear finite element analyses (NLFEA) at the design stage is not a feasible alternative, at least for current structures. NLFEA are time consuming and require advanced software and knowledge. However, this type of analysis is a useful auxiliary to understand the behaviour of the structure of this design challenge. The internal efforts in a restrained structure subjected to imposed deformations are strongly dependent on the stiffness reduction caused by cracking. These effects can be taken into account by using constitutive models for concrete including the effects of maturity, creep, shrinkage and cracking.

4.1 FE modelling approach

The reference method for assessing the nonlinear, time-dependent, behaviour of the structure is the one shown in reference [6]. The slab is discretized by using 8-node shell finite elements, numerically integrated along the thickness, with resource to the software DIANA [7]. The concrete behaviour is simulated through a smeared cracking approach. A multiple-fixed-cracks model, with strain decomposition, is used. In this type of model, the total concrete strain is equal to the sum of: elastic instantaneous strain; creep strain; shrinkage strain; temperature induced strain; crack strain. The constitutive models to simulate the concrete behaviour are explained in reference [8].

A tension stiffening diagram is used to model the average stress in concrete, in cracked regions. Tension stiffening diagrams are suitable to simulate the concrete behaviour using coarse FE meshes, this being the approach followed in this work (see the mesh in Figure 6). One of the advantages of this modelling approach, with coarse meshes, lies on its robustness: converged results are easily reached. Another advantage is the fact that the stiffness of cracked concrete is defined in a consistent way with respect to the models proposed by design codes such as the fib Model Code [9]. The average stress in cracked concrete, owing to tension stiffening effects is, in these NLFEAs, simply taken as $k_t\ f_{ctm}$, where f_{ctm} is the average tensile strength of concrete and k_t is a tension stiffening coefficient, equal to 0.4.

It is important to understand that the crack opening is not a direct output of the NLFEA, given that a tension stiffening approach is being followed. In order to get the crack opening value, the crack strain, ε_{cr} (which is a direct output of the NLFEA) has to be integrated over a length equal to the crack spacing, $2\ l_{s,max}$. In this work, the crack spacing $2\ l_{s,max}$ is quantified based on the equation proposed by the fib Model Code [9]. A simple way to get the crack opening, w_d, consists, therefore, in averaging the ε_{cr} output values over the crack spacing length. Once the average crack strain, $\varepsilon_{cr,mean}$ is computed, the crack opening w_d is simply calculated as:

$$w_d = 2\ l_{s,max}\ \varepsilon_{cr,mean} \tag{1}$$

where $\varepsilon_{cr,mean}$ is the aforementioned average crack strain value.

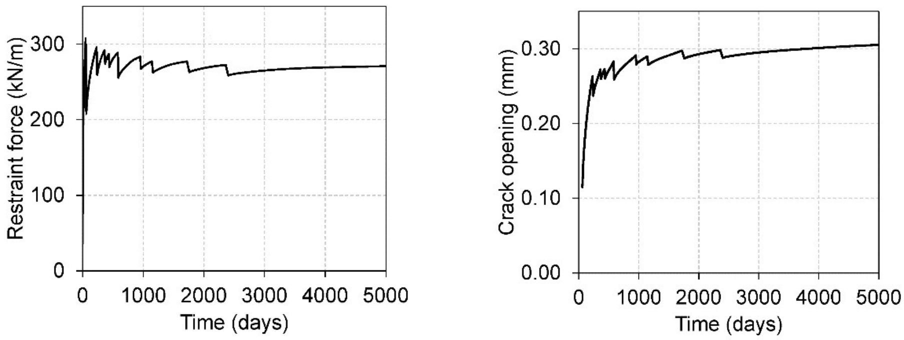
The ultimate purpose of the NLFEAs is the determination of the reinforcement required to get a maximum crack width of 0.30 mm. This reinforcement has to be determined iteratively. That is, the NLFEA has to be repeated using, in each analysis, a different amount of reinforcement. An iteration is, in this context, a NLFEA using a certain amount of reinforcement. The iterations have to be continued until the specified crack opening value (0.30 mm in this case) is reached. A very small number of iterations (~4) is needed if the reinforcement adopted in iteration i+1 is quantified based on engineering calculations using the internal efforts (axial force and bending moment) obtained in iteration i. The explanation of such engineering calculations is out of the scope of this presentation.

4.2 Challenge 1

The FE model to analyse Challenge 1 consists on a single longitudinal strip of FEs, i.e., one strip taken from the model shown in Figure 5. Owing to the absence of any bending effect, the axial force in such strip is constant throughout the entire model. Therefore, the different tensile strength values have to be assigned to the various FEs. Otherwise, the entire structure would crack simultaneously, and the actual crack formation sequence would not be simulated. The adopted tensile strength values are as follows: 2.10 MPa for the FE with lowest strength; increments of 0.02 MPa for the remaining FEs. At the end of the analysis, the total number of cracked FEs was 8, i.e., the cracked region is ~ 1/3 of the total model.

After iterating to reach a maximum crack opening of 0.30 mm, the required area of reinforcement was obtained: top and bottom reinforcements equal to 7,2 cm^2/m. Figure 4 shows relevant results of the NLFEA: the restraint force (axial for in the slab due to the total end restraint) and the crack opening in the first formed crack. It interesting to note that, even though the maximum force occurs in the first ages (upon the formation of the first crack), the maximum crack opening is obtained at long term. This is due to the evolution of concrete shrinkage and its effects on the slip between concrete and steel. As mentioned in §4.1, the presented crack opening is the product of the crack strain (output of the NLFEA) and the crack spacing (equal to 349 mm, according to the fib Model Code [9], for 10 mm reinforcement bars).

As shown in Figure 4a, the axial force in the slab, at long term, is 272 kN, which is 82% of the bare concrete cracking force ($A_c\ f_{ctm}$ = 330 kN).



a) b)

Figure 4: Results of the NLFEA for Challenge 1: a) time variation of the restraint force (axial force in the slab); b) time variation of the crack opening for the first formed crack.

4.2 Challenge 2

Figure 5 depicts the FE model for Challenge 2. The tensile strength is uniform throughout the entire model, equal to f_{ctm} = 2.2 MPa. Unlike Challenge 1, in this case the tensile stresses are not constant, owing to bending effects. By iterating in order to reach a maximum crack opening (at the concrete surface, the control position specified in the fib Model Code [9]) of 0.30 mm, the following reinforcement quantities are reached: 11,0 cm^2/m at the top and 8.9 cm^2/m at the bottom surface. Figure 6 shows the crack patterns at long term (5000 days after casting), at the top and bottom slab surfaces. In the image, the crack strains are represented by vectors perpendicular to the crack.

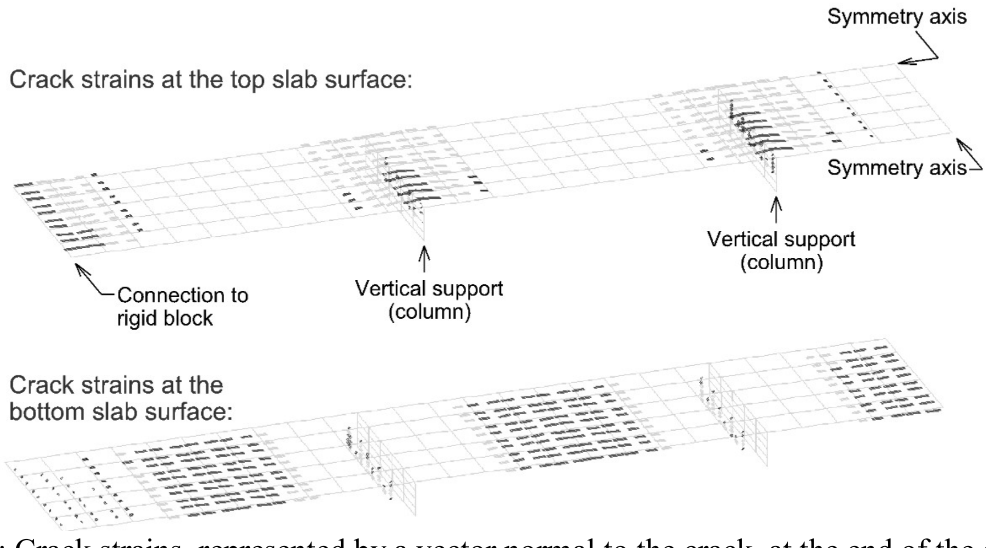


Figure 5: Crack strains, represented by a vector normal to the crack, at the end of the analysis.

As regards the restraint force, it is important to note that there is a significant decrease (owing to bending effects) with respect to the results of Challenge 1. In Challenge 2, at long term, the axial force in the slab is ~ 150 kN/m (45% of $A_c\ f_{ctm}$). This value corresponds to the average over the slab width.

5. CONCLUSIONS

The design challenge, proposed to various design offices and teams, was briefly presented. It focuses on the cracking control and structural behaviour of structures submitted to restrained deformations and imposed loading. Then, nonlinear finite element analyses were used to analyse the structures' behaviour. Very important differences, in the results reached by different design teams, were observed. These differences have very important economic implications in the design of large restrained structures. This issue deserves attention by the scientific and practitioner communities, in order to improve the experimental validation of design methods and also to produce clear and feasible design procedures for restrained structures.

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