Eco-resilient (ECORE) concrete constructions: a new challenge and a new concept

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Abstract. This paper presents a new concept concerning the development of eco-resilient concrete constructions, that is to say constructions with a reduced carbon footprint and which can withstand mechanical stress and physico-chemical attacks worsened by climate change. After a critical analysis of current research and development policies in the field of concrete construction, a new global approach is proposed which should allow this concrete construction profession to better respond to the challenges caused by global warming. This approach is based on two strong ideas: 1) the use of fiber concretes in combination with passive or active reinforcement in all constructions susceptible to crack 2) the use of numerical models based on non-linear finite element calculations in order to optimize the design of eco-resilient concrete constructions. This paper focus on a numerical modeling, which has been, in the past, experimentally validated to give relevant information concerning the cracks opening of the FRCs constructions when their service limit state is concerned. It proposes, also, an example of use of this numerical model for optimizing FRC concrete construction in order to reduce its carbon footprint.

Keywords: Concrete constructions, Fiber reinforced concretes, Ecological, Resilient, Design optimization, Finite element models

Introduction

Climate change has different origins and consequences. Concrete constructions contribute to its origins and suffer from its consequences. Due to the high carbon footprint of cement, the main component of concrete, they are a significant contributor to global warming (not to mention the consumption of natural resources). As the most widely used material in the construction industry, concrete constructions fall victim to climate change. Indeed, climate change leads to exceptional and frequent natural risks. Among these risks, we can mention, non-exhaustively, floods, coastal flooding, earthquakes, and fires. All of these lead to severe mechanical and physical aggressions that these constructions must resist. The most significant aggressions include dynamic stresses (shocks and earthquakes), temperature variations (day/night, summer/winter), humidity variations (rain/drought), water penetration (floods), and very high temperatures (fires). Concrete constructions must therefore become increasingly resilient. The main aspect of this resilience is related to the design of these constructions, which must enable them to withstand with minimal damage. This is important, as rapid, cost-effective repairs that are resource-efficient are the best candidates for sustainable development. In conclusion, today's and tomorrow's concrete constructions must be ecological and resilient or eco-resilient (ECORE constructions). These two objectives are not so easy to achieve. The current research and development in the field of concrete constructions is an illustration of this. This article aims to offer a critical analysis of current research and development in the field of concrete constructions and to propose a more relevant global approach to address the challenge posed by climate change: building with concrete in an ecological and resilient manner.

1 Critical analysis of current research and development in the field of concrete constructions

2.1. Research at the material scale.

Research and development, considered at the international scale, has mainly and strongly focused in recent years on the ecological aspects of concrete with the primary objective of reducing its carbon footprint. To achieve this, studies have focused on the development of concrete formulations containing less cement, by replacing this cement with powders that have lower carbon footprints than cement and/or come from recycled materials. They have thus focused on aspects related to rheology (workability), durability, and basic mechanical behaviors (compressive and tensile strengths) of these new "ecological" or alternative concretes.

However, it should not be forgotten that a construction material has no other purpose than to be used in the construction of a building (this is obvious). It is therefore the building itself that must be ecological, and concrete is only a means to achieve this.

Concrete construction becomes "ecological" by reducing the amount of cement it contains while ensuring the functions it is required to perform.

As previously mentioned, due to climate change, concrete constructions are subjected to increased mechanical constraints and physico-chemical aggressions. Understanding the cracking process of these constructions is a major issue to consider in light of these aggressions, because:

- The cracking process of concrete subjected to impulsive solicitations (such as shocks) or seismic type solicitations (which fall within the scope of plastic fatigue) is very different from that related to quasi-static solicitations.
- So-called service cracking (crack openings not exceeding, normally, 300 µm) constitutes a very important accelerator for the penetration of aggressive liquids (water containing aggressive ions) for both concrete and reinforcements present in load-bearing structures, such as passive reinforcement of reinforced concrete or active reinforcement of prestressed concrete.

However, determining the tensile and compressive strengths of concrete does not provide relevant information on the static cracking process, let alone under seismic or dynamic (shock) solicitations of a construction made of this concrete. Only the use of fracture mechanics theory allows access to this relevant information.

Consequently, current research on alternative concretes are not enough relevant to meet the challenges of climate change.

2.2. Research at the structural scale.

As mentioned previously, it is the concrete construction itself that must be ecological. In other words, this construction must minimize, for given functions, the amount of cement of which it is made. This minimization necessarily involves the choice of the design method chosen for the construction.

Nowadays, concrete constructions are predominantly dimensioned through the use of design standards (in Europe, the Eurocodes). They were established at the beginning of the 20th century to allow numerous design offices around the world to quickly and as safely as possible design concrete constructions. These design standards are based on fairly rudimentary simplified approaches compared to the real mechanical and physico-chemical behaviors of concrete constructions. This is one of the main reasons why they involve numerous so-called safety factors, which aim to compensate for the shortcomings present.

The problem, in light of current challenges, is that these safety factors generally lead to significantly oversizing concrete constructions, without always oversizing them for safety. In other words, the design standards lead to an overconsumption of concrete and therefore cement.

Today, a large majority of national and international working groups concerning the design of concrete constructions are working on improving the design standards.

3. Proposal of a global approach to the design of ECORE concrete constructions.

In order for concrete constructions to improve their resistance to mechanical and physico-chemical aggressions related to climate change, they must improve their resistance to cracking in the face of these aggressions.

It is now known and accepted that fibers, especially steel fibers, contribute significantly to controlling this cracking (research on this subject is completely clear and mature). Thus:

- They are more effective than reinforced concrete reinforcements in controlling service cracks. For the same service solicitation, the cracks are less open, more tortuous in their path, and often discontinuous in the presence of fibers. Concrete constructions thus resist the penetration of liquids much better.
- Fibers associated with reinforced concrete reinforcements significantly improve the behavior of concrete constructions under shock and seismic loads.

These positive contributions of fibers are linked to the fact that they act on a different scale than the cracking process of concrete and are complementary to considered classical reinforcements (passive and active reinforcements).

Fibers must be considered as indispensable as these classical reinforcements today.

Fibers must be used in all concrete constructions for which their functions are penalized by cracking.

The addition of fibers thus leads to an improvement in the resilience of concrete constructions, but does not necessarily meet the objective of improving the ecological performance of these constructions. To achieve this, their design must result in a significant reduction in the quantity of cement used, as well as in the quantity of reinforcements and fibers.

Constructions with hyperstatic mechanical behavior are those that lead to greater safety when they are subject to cracking. This fact is linked to a much less localized cracking process (due to stress redistribution) than that related to statically isostatic constructions, especially when it comes to service cracking.

As previously mentioned, design standards for concrete structures are too rudimentary to realistically consider the multiple cracking mechanisms of hyperstatic structures, whether they are reinforced concrete structures or fiber reinforced concrete structures, and even less so when it comes to a mixed reinforcement composed of rebars and fibers. They cannot lead to an optimized design of these structures.

The solution can only come through the use of nonlinear finite element analysis, i.e., considering the cracking processes of concrete constructions.

There are a number of numerical models in the literature that have this objective. The main problem in using these models for an optimized design (in terms of shape, geometry, and dimensions) is that they are currently insufficiently validated at the scale of real structures.

In the past, numerous experimental studies were carried out internationally on structures or structural elements at the full scale. The main objective of these studies was to show that the design standards were relevant with regard to their ultimate state resistance.

Today, similar test campaigns must be carried out. However, this time, their objective must be to convincingly validate these numerical models with regard to their ability to qualitatively and quantitatively consider the cracking processes at the service and ultimate limit states of structures.

If this objective is not considered a priority in the field of concrete constructions, it is unlikely that the concept of eco-resilient (ECORE) constructions will develop.

In the following chapters are presented, first a numerical model which has been, in the past, experimentally validated and, secondly, an example of use of this numerical model for optimizing FRC concrete construction in order to reduce its carbon footprint.

4. Numerical models

4.1. The probabilistic explicit cracking model

The probabilistic explicit cracking model was developed to analyze the cracking process of concrete [1, 2]. The numerical model is deeply detailed in [1, 2]. It is based on the following physical assumptions:

- The material being considered as heterogeneous, its local mechanical characteristics are randomly distributed.
- These mechanical characteristics are scale effect dependent. It means that they depend on the volume of material considered [3].

From mechanical and numerical points of view, it can be summarized as following:

- Each volume element of the mesh represents a volume of heterogeneous material.
- Tensile and shear strengths are distributed randomly over all elements of the mesh [1, 2].
- Cracks are simulated by using non-linear interface elements (quadratic elements). Failure criteria of Rankin in tension and Tresca in shear are used. Once one of these failure criteria is reached, the interface element is considered as opened simulating a crack creation. The tensile and shear strengths as well as the normal and tangential stiffness values of the element are then set equal to zero.

4.2. The probabilistic explicit cracking model for FRC

The complete bridging action of fibres inside the cracks was simulated as following [4]:

- Normal and tangential stresses in the interface element linearly increase with normal and tangential displacements to simulate the elastic bridging action.
- This elastic action of fibres exists until a threshold value related to the normal displacement. From this threshold value, the normal stress linearly decreases with the normal displacement. That is to consider the damage of the bond between the concrete and the fibre. This decreasing evolution is considered through a damage model.
- Finally, when the normal displacement reaches a second threshold, the action of fibres is considered negligible and so, the interface element is considered definitively broken. Its normal and tangential rigidities are then set to zero.
- The post-cracking energy, dissipated during all the bridging action of the fibres, is randomly distributed over the finite element mesh. This random distribution is a log-normal distribution function with a mean value independent of the mesh elements size and a standard deviation increasing as the mesh elements size decreases. This choice is in perfect agreement with the experimental results [5].

To analyze the cracking process in a real FRC structure, the way to determine the values of the model parameters of the fibres action is the following:

- The mean value is determined from experimental results related to uniaxial tensile tests on notched specimens.
- The standard deviation is determined by an inverse analysis approach. As the mean value of the post-cracking energy is known, the inverse approach consists of simulating the uniaxial tests with different element mesh sizes. For each element mesh size, several numerical simulations are performed. The standard deviation related to each mesh size is the one that best fit the experimental results (from uniaxial tensile tests). This inverse approach allows to determine a relation between the standard deviation and the finite element mesh size.
- The two threshold parameters, evocated above, are also obtained by performing an inverse approach. It consists in fitting the post-cracking behaviour of the uniaxial tensile tests this by using the simplified triangular stress-displacement curve of the model.

It is important to consider that extension of the probabilistic explicit cracking model to FRC were validated for different structural problems [4, 6, 7]. These validations were focused on the relevancy of the model to determine cracks spacing and opening even for opening cracks less than 300 microns.

The model is schematically summarized in Figure 1.

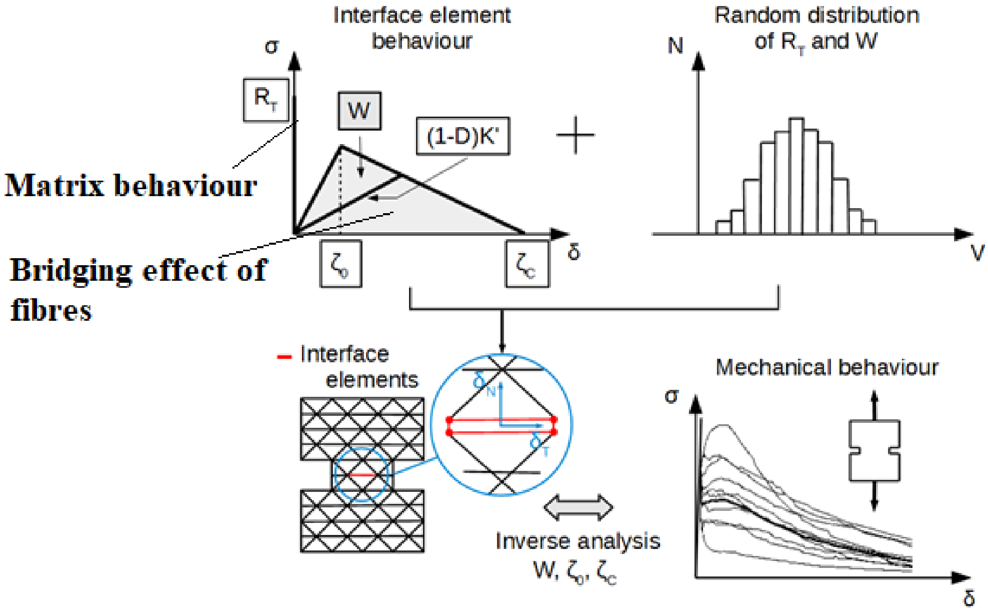

Figure1. Probabilistic explicit cracking model for FRC

The probabilistic explicit cracking model have been recently used for optimizing FRC track slab in order to reduce its carbon footprint [8].

This example of use is presented in the following chapter.

5. Design optimization of FRC track slab

All the study, briefly presented in this chapter, was presented in detail in an international conference [8]. Between 2007 and 2014, a new concept of railways track called New Ballastless Track (NBT) was developed [9]. This concept is based on two superimposed independent layers of concrete slabs (i.e. foundation and track slabs) and was designed to achieve a 100 years life span under a mixed high speed and freight traffic. It was validated under 10 million fatigue cycles on a real-size mockup [9 - 11].

Figure 2 presents the original concept and the geometry of the experimental mock-up. In this figure, the upper track layer is made of reinforced concrete (C35/45) called BC5 while the foundation slab is made of plain concrete (C25/30) called BC3. An elastic layer was used to reproduce the mechanical reaction of the ground simulating the soil bearing capacity.

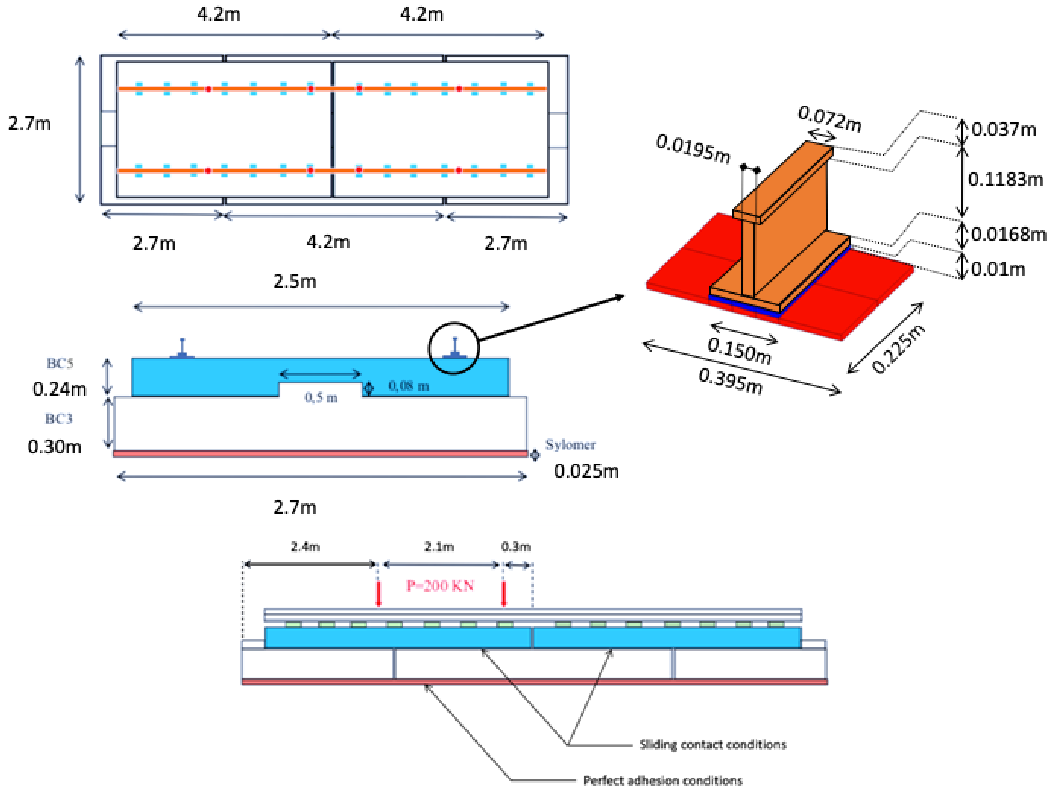

Figure 2. Geometry and dimensions of the Railway Track Mockup.

A first numerical study [12] was performed to evaluate the possibility of replacement of the original reinforced concrete layer BC5 of the track slab by a steel fiber reinforced concrete. This numerical study was performed by using the probabilistic explicit cracking model.

The comparison between the two technical solutions was made by analyzing and comparing their respective cracking process.

The principal conclusion related to this first numerical work were the following: the use of 78 kg/m^3 of fibres is mechanically more efficient than the usual ratio of rebars.

The second conclusion was the following: if this technical solution is adopted, it is preferable to use, in zones of high concentration of tensile stresses (it means in the upper track layer, B3, at the vertical of the joints of the foundation slab, B5), some local rebars to ensure a necessary level of safety to the structure.

After this first study, a second one was performed with the objective to optimize the design of the FRC railway track to decrease its carbon footprint.

To reach this objective, the following strategy of optimization was followed:

- *Step 1 - First level of optimization*: different dosages of fibres from 40 to 78 kg/m3, different sectional percentages of bottom rebars from 0 to 8.8% and different thicknesses of the upper track layer (B3) from 15 to 24 cm were considered. The rebars, with an arbitrarily length of 40cm, were placed in zones of high concentration of tensile stresses as in the first study [12]. 20 technical solutions were analysed and compared. Acceptable solutions were those leading to maximal crack openings smaller than 100 µm. It was the maximal value allowed by the industrial for this application that corresponds to a service limit state design. The numerical model used being a probabilistic one, between 10 and 30 simulations were performed for each technical solution studied.

- *Step 2 - Carbon footprint evaluations*: carbon footprint evaluation was performed for the technical solutions resulting from step 1.

Erreur ! Source du renvoi introuvable. presents only the technical solutions considered as acceptable, it means the technical solutions leading to average crack openings less than 100 µm.

Table 1: All acceptable technical solutions (step 1)

Concrete slab heigth (cm)	**Steel reinforcement (%)**	**Fibre content (kg/m^3)**
22	7.93	76
24	4.41	64
17	4.41	68
22	5.29	64
22	5.29	76
22	7.93	64
24	8.81	80
15	17.6	72

Figure 3 shows an example of a crack pattern obtained with one technical solution studied

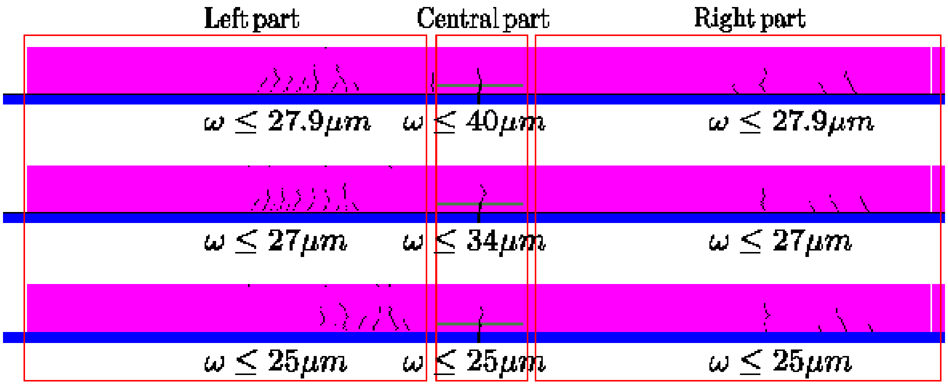

Fig. 3: Example of cracking patterns related to technical solution – 3 different simulations.

Carbon footprint evaluations

Comparison of carbon footprint evaluation concerning the classical solution of railway tracks reinforced only with rebars [8] and that of railway tracks reinforced with a mix of steel fibres and rebars was made. This comparison was based on some data from literature [13] given in Table 2.

Table 2. CO_2 emissions per slab's constituent. (*) As an order of magnitude, CO_2 emissions per concrete m^3 are between 200 and 300kg/m^3. (**) Values from [13].

Concrete	**Fibres**	**Steel reinforcement**
250 kg/m^3(*)	2.425 kg/t(**)	1.932 kg/t(**)

Table 3 summarizes the carbon footprint evaluation of acceptable technical solutions. CO_2 amounts are calculated for one slab using Table 2.

Table 3. $\mathrm{CO_2}$ emissions per technical solutions. The gain, in $\mathrm{CO_2}$, emitted was expressed here by comparison with the classical solution. The minus sign denoted a reduction in $\mathrm{CO_2}$ emission.

Technical solution number	7	9	14	15	16	19	20
$\mathrm{CO_2}$ (t)	57.8	63	57.7	57.8	57.7	63.0	39.4
Gain (%)	-8	0	-8	-8	-8	0	- 37

Results showed that the most significant part of the emission gain was related to the reduction in concrete's volume. It could be noted that a simple reduction in slab's height of 2 cm (22 cm instead of 24 cm) leads to a non-neglectable reduction of quite 10% of $\mathrm{CO_2}$ per slab. It represents in fact around 5.2 t of $\mathrm{CO_2}$, an amount that can become important for the entire railway line.

Solution number 20, that is a lot of more innovative, appeared very interesting and promising since it allows a much larger reduction of $\mathrm{CO_2}$ emission (-37% compared to the classical solution).

6. Conclusions

This paper focuses on the fact that, in the future, a very good technical solution to conceive eco-resilient concrete constructions is to use both fiber reinforced concretes and numerical tools (finite elements methods) as design tools.

It presents a model capable to give precise information on the cracking process of SFC constructions in the framework of the limit service state situation. This model is the probabilistic explicit cracking model.

An example of study in which this model was used is presented. This study was on the optimization of the design of steel fibres reinforced railway track to decrease the carbon footprint related to this type of construction. Even this study was very partial and incomplete, it presents, very well, the great potential of this type of numerical model for optimizing the design of eco-resilient constructions.

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