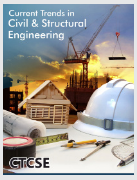

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Review Article

True Compression Behavior of Concretes and Fiber Reinforced Concretes

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Abstract

The main objective of this paper is to focus on the fact that the cracking process of concretes and fiber reinforced concretes, FRCs, in compression is more complex than what is usually admitted in the literature. It is also emphasized that standard compression tests, subject to significant artifacts, are unsuitable for determining the reliable and safe compression behavior of these materials. This article insists on the fact that, if the use of these standard compression tests is acceptable within the framework of the codes, as Eurocode 2, which use important safety coefficients, it is not the same for their use within the framework of more sophisticated numerical models, as the non-linear finite elements models. To calibrate the parameters of the compressive behavior law of these numerical models, it is proposed to implement a strategy based on the use of an inverse analysis applied to a bending test on reinforced concrete, or FRC, specimen.

Keywords: Concretes; Fiber reinforced concretes; Compressive behavior; Cracking process; Standard test; Numerical models

Introduction

The compression behavior of concretes as well as their Young's modulus are considered as the basic mechanical characteristics of these materials. The determination of the compressive strength of concretes is at the origin of various standard tests according to the countries, this for a very long time. These tests, in the context of codes but also in the context of sophisticated numerical modeling using non-linear finite element models, are used without hesitation. In fact, the cracking process of concretes but also fiber reinforced concretes, FRCs, is much more complex than it seems. This paper describes, in detail, this process and demonstrates that the standard tests are, in fact, because of the experimental artifacts they generate, poorly suited to determining a reliable behavior law for these materials in compression. It also studies how the inadequacy of these tests impacts the design of concrete and FRC structures when using numerical models.

Concrete Cracking Process in Compression

This cracking process can be described as following [1]:

Step 1: Creation and propagation of diffuse microcracking.

Firstly, it is important to recall that, in concrete, a crack is created only if tensile stresses are present. In the case of compression, these tensile stresses are generated by the coexistence of the Poisson's coefficient and the very strong mechanical heterogeneity of concrete (the mechanical characteristics of the cement paste are very different from that of the aggregates). This coexistence leads to the fact that the preferential orientation of these tensile stresses within the material is perpendicular to the direction of the compressive stress and to the appearance of microcracks parallel to the direction of the compressive stress. These microcracks opening, that depends on the Poisson's coefficient, is very small and does not disturb the mechanical behavior of the concrete specimen that remains elastic.

Step 2: Propagation of vertical microcracks and appearance of a certain number of long vertical cracks

It is important to emphasize that the evolution of microcracking is controlled by the strain perpendicular to the direction of the stress. This strain generates (as it is said previously with reference to the Poisson's ratio and the heterogeneity of the material) the local tensile stress field necessary for this evolution (propagation of microcracks). It is therefore indirect control at the local scale, i.e. at the scale of the aggregates. The microcracks lead, during their propagation, to the creation of a certain number of long vertical cracks (vertical macrocracks). These long vertical cracks are positioned throughout the volume of material stressed. It is interesting to note two important points relating to this state of cracking:

- The long cracks opening is very small (not visible to the eye). Indeed, this opening is linked to the value of the Poisson's ratio and the number of vertical cracks.
- The vertical strain (i.e. in the direction of the compressive stress) is not affected or very little by the existence of these long cracks. Indeed, they cut the volume of material into a certain number of small columns through which the stresses and the strains remain elastic (or quasi elastic).

In other words, those long "invisible" cracks do not affect much more the mechanical behavior of the volume of material solicited than the microcracks initially created. It means that the volume of material remains macroscopically quasi-linear elastic under monotonic stress increasing. During this step of creation of long vertical cracks, a lot of elastic energy is consumed. That is not the case for the cracking process related to the tensile behavior of concrete. Indeed, during this cracking process only one macrocrack is created after a short step of diffused microcracking [1, 2]. It is the reason why the creation of vertical macrocracks during a compression test requires much higher stress levels than those necessary for the creation of the localized macrocrack during the process of tensile cracking. It is this difference in the dissipated elastic energy (consumed in the creation of cracks) that explains the difference that exists between the compressive strength of a concrete and its tensile strength.

Step 3: Creation of oblique microcracks.

No material can accept increasing stresses without trying to "escape" it. For example, many metals escape stress by creating movement of dislocations (which is the physical origin of the so-called plastic behavior of metals). As far as concretes are concerned, this "loophole" is physically expressed in a different way. To understand this phenomenon, it is necessary to focus the observation on the scale of the columns created during stage 2 of the cracking process. At this scale, the small columns do not cut the stressed volume of concrete in a way geometrically perfect. Indeed, they present tortuous and asymmetrical surfaces and, therefore, undergo some local compound bending under the effect of the overall compressive stress. This local compound bending added to the very significant heterogeneity of the material at this scale (it suffices to imagine the presence of aggregates inside the columns!) generates oblique microcracks inside the columns (oblique with respect to the columns main direction). This step 3 of the cracking process, due to the very small size of the oblique microcracks, does not modify the global behavior of the volume of concrete stressed which remains quasi-linear elastic.

Step 4: Transition phase or beginning of the oblique microcracking localization process.

This step 4 concerns the propagation of the oblique microcracks inside the columns to form oblique mesocracks, it means cracks crossing the columns. The propagation of microcracks inside the columns is accompanied by a significant creation of friction between the lips of the microcracks (due to the tangential displacements of these lips), friction that does not exist in the tensile cracking process [1, 2]. These frictions have the consequence of generating a strong dissipation of energy and, so, of non-linear vertical strain at the scale of the concrete specimen.

Step 5: Localization of oblique macrocrack.

A number of oblique mesocracks propagate stably (due to the existence of frictions). Then, one of these mesocracks ends up dominating the others to lead to the creation of an oblique macrocrack. The propagation phase of the oblique microcracks, followed by that of the oblique mesocracks which ends with the creation of an oblique macrocrack, is accompanied by a strong dissipation of energy by friction which completely explains the non-linear behavior concrete in compression. The creation of this localized oblique macrocrack coincides with the peak load of the compression test and so with the compressive strength of the concrete.

Step 6: Propagation of the oblique macrocrack.

This step corresponds to the structural behavior of the concrete specimen loaded in compression and no more to an intrinsic material behavior in compression. During this step the post-localization (or post-peak) behavior of the specimen is a softening one. Due to the existence of important frictions inside the lips of the oblique macrocrack during its propagation, the post-peak behavior of concrete in compression is less brittle than in tension. When the oblique macrocrack propagates, its lips undergo tangential displacements. These significant displacements have the consequence of opening the large vertical cracks, created during step 2 and thus make them visible to the naked eye (whereas they were until then invisible). Finally, the concrete specimen fails when one the oblique macrocracks crosses it.

Influence of the Boundary Conditions During a Standard Compression Test

In practice, when performing a compression test without taking particular precautions at the interface between the concrete specimen and the platens of the press, a restrain phenomenon

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appears at the ends of the specimen, leading to test artifact. This restraint leads to a significant stress field disturbance at the level of the specimen ends and to an increase of the shear stresses in these specimen zones [3]. So, the oblique microcracks, mesocracks and macrocracks are more numerous in these specimen zones. This restrain leads also to a strong confinement of oblique cracking due to a very strong increase in the friction forces between the lips of these oblique cracks. The propagation of the macrocrack is then prevented and, depending on the intensity of the restrain and the position of the first macrocrack, one or more other macrocrack(s) may appear at the specimen ends. This situation has two mechanical consequences:

- The force applied to the specimen increases. This leads to an overestimation of the compressive strength.
- The frictional forces being increased and a significant overestimation of the non-linear behavior of concrete is also observed.

So, the compression test, thus carried out, leads to overestimate the strength as well as the ductility of a concrete under compression.

Modeling of the Compressive Behavior of Concrete

If the cracking process of concrete in compression is considered (chapters II and III), it appears clearly that:

- The post-peak behavior is not a material property but a structural one.
- The boundary conditions related to the experimental test led to overestimate the compressive strength and the ductility of the concrete.
- Only, the quasi-linear elastic part of the experimental curve (obtained by performing a compression test disturbed by the boundary conditions) can be strictly considered as an intrinsic material property.

The problem is that the large majority of compression tests, which are standard tests, used to determine a compressive behavior law, are affected by these boundary conditions.

So, the way of modeling this compressive behavior is very questionable. Presently, two main modeling approaches are considered in literature:

- Analytical relations in codes (in Eurocode 2, as example),
- Finite elements models.

The first approach is based on the very well-known method of balance of a cracked section. In case of this approach, a simplified model curve is arbitrary adopted from the knowledge of the experimental one. This simplified model curve is “built” from the experimental curve by using some safety coefficients that lead to underestimating, a lot, the compressive behavior obtained from the test. So, it can be considered that, until the peak load, the standard approach is rather safe. In the second family of approach are the diffused cracking models [4-12] and the cohesive crack models [13-15] that are the most used in literature. In these numerical models, the compressive behavior law (stress-strain relationship) used is mostly determined from the experimental curve. It means that the model parameters are fitted from the experimental curve including the post-peak part of this experimental curve. So, if chapters II and III are considered, it can be stated that it is wrong to proceed like this. It exists, in literature, another numerical model using finite element method called probabilistic explicit cracking model [16-18]. This model considers the creation and the propagation of cracks by using interface elements (special element with very small thickness, no fare from zero). These interface elements open when two failure criteria are reached at the gravity point of the elements creating by this way cinematic discontinuities (that represent very well real cracks). One of these failure criteria is based on random parameters depending of the element size. By this way, the model considers the strong mechanical heterogeneity of concretes and the scale effect existing in the cracking process of concretes [19].

Concerning the failure criteria, they are the following:

- The first failure criterium is related to an elastic perfect brittle behavior in uniaxial tension. It is this criterium which introduces random parameters depending of the elements size.
- The second criterium is related to an elastic perfect brittle behavior in shear. This one introduces only deterministic parameters.

It is important to precise that, in the model, a friction law is considered between the crack lips after its creation (due to the activation of one criterium) [18]. If the development history of this numerical model is concerned, it can be noted that the shear criterium and the friction law were introduced only to consider the zones of a concrete structure strongly stressed in compression [18]. Indeed, it has been clearly shown, that in the majority of cases, cracks propagate in mode I, even shear cracks propagation is concerned [20, 21]. To summary, only this probabilistic explicit cracking model is capable to consider all the steps of the cracking process of concrete in compression. It has been successfully validated in the past [18, 20].

Case of Fiber Reinforced Concretes

First of all, it is important to recall that fibers act, by bridging effect, only on active cracks. It means that fibers intervene on the cracking process of concretes only if the lips of the cracks have displacements in mode I, (the fibers are very efficient, in this case) or in mode II (the fibers are less efficient, in this case) [20]. So, to analyze the mechanical behavior of fiber reinforced concretes, FRCs, in compression, the best way is to analyze the bridging effect of fibers during the different steps of the cracking process of concrete in compression (chapters II and III). As evocated above, this bridging effect is effective only when the cracks are sufficiently active. If this cracking process is concerned (chapter II), it appears clearly that cracks fulfill this condition from step 5. It means that fibers can, by bridging effect, act on the crack’s propagation when one oblique mesocrack propagates to create one oblique macrocrack. This action is not very important because linked to the bending behavior of fibers (displacement of the crack lips in mode II) [1, 20]. In fact, the bridging effect of fibers becomes to be really

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effective during the oblique macrocrack propagation and, above all, during the long vertical cracks opening (step 6) that introduces displacement in mode I. To summary, fibers are efficient for bridging the cracks during the structural behavior of the specimen and cannot increase significantly the concrete compressive strength [1]. That happens if there are no test artifacts linked to the boundary conditions (chapter III). If these artifacts occur, the influence of the fibers bridging action is modified. Indeed, if these artifacts occur, the role of fibers is more complex. First of all, the number of oblique mesocracks and macrocracks (steps 5 and 6 of the cracking process) being more important near the platens of the press, the bridging effect of fibers during these steps of cracking is also more important. So, the compressive strength and the ductility in compression of FRCs are artificially increased by the existence of these test artifacts. These artificial increases are greater than for concretes (it means, without fibers).

So, all the results from literature which indicate that the compressive strength and the ductility in compression of FRCs increase with the percentage of fibers is wrong [1]. Secondly, during the post-peak behavior (step 6 of the cracking process), it means the structural behavior in compression, the bridging effect of fibers on the long vertical cracks that opens in mode I is very important. That leads to improvement a lot of this post-peak behavior. If the models related to the compression behavior of FRCs are concerned, the following comments can be done:

1. The codes, like the Eurocode 2, whose the main objective is to propose simple and safe design methods, have to keep, for the compression behavior, the same analytical relations as for concretes (without fibers).

2. The numerical models as the damage and the smeared crack models are unsafe if they calibrate, they model parameters from results obtained by performing classical standard compression tests.

Discussion

With the exception of bridge pillars or building piles, a relevant design for reinforced concrete structures must avoid their failure in shear and in compression because these failures are very brittle. It is for that reason that enough steel rebars are used to prevent these types of failure. So, even though the codes are very simplistic (physically speaking) concerning the modeling of the compression behavior of concretes, they achieve their objective. Concerning the FRC structures, if the codes conserve the same compression behavior of FRC as for concretes, the safety degree will be improved. The aim for using non-linear numerical models is to propose a more physical approach for structural design. By this way, the objective is to eliminate, or to decrease, the safety coefficients used in the codes and, so, to obtain better optimization of the design of the concrete structure. It is the main contribution of the non-linear numerical models in the domain of eco- construction [22]. If the previous chapters are considered, it appears that this objective is not achieved in a good way if the model parameters related to the compression behavior of concretes or FRCs are calibrated from the compression standard tests. In this case, the safety design of the structure is not sufficiently guaranteed. The best way to improve the calibration of these models in relation to concretes and FRCs compression behavior is to perform an inverse approach linked to an appropriate experimental test.

The proposal

First of all, it is necessary to define the type of mechanical test which can give adequate experimental information about the compression behavior of concretes or FRCs. The simplest one is a four-points bending test on small, reinforced beam. The reinforcement consists of rebars located in the tensile zone of the beam. These rebars are dimensioned to cause a failure in compression of the beam. The load-deflection curve is the experimental result useful for performing the inverse analysis. Indeed, if the numerical model is previously validated to analyze the mechanical behavior of the reinforced beam when cracks start from the tensile zone of the beam (this is the minimum required for this type of model), it is relatively easy to calibrate the model parameters related to the compression behavior of the material.

Conclusion

After a fine analysis of the cracking process at the origin of the behavior in compression of concretes and FRCs, this paper shows that the standard tests for determining the compression behavior are disturbed by important artifacts related to their boundary conditions. These artifacts lead to overestimating the compressive strength and ductility of concretes and even more that of FRCs. It is also underlined that these overestimates have little impact on the design of concrete structures carried out with the codes. This is linked to the large safety factors used in these approaches for concretes. On the other hand, concerning FRCs, an original proposal is presented in this paper. It concerns the fact of keeping, for these materials, the same behavior law in compression as for concretes. This choice makes it possible to be sure to be on the safety side. Finally, it is underlined that the overestimates have a non-negligible impact when non-linear numerical models are used to optimize the design of concrete structures and more specifically of FRC structures. They can lead to unsafe designs. To solve this problem, it is proposed to calibrate the parameters of these numerical models for the compression behavior by performing a more adequate strategy (than to perform standard compression tests) based on an inverse approach and the use of a bending test on a reinforced beam (designed to fail in compression).

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Conflict of Interest

No conflict of interest.

References

1. Rossi P (1998) Metal fiber concretes. Les Presses de l'Ecole Nationale des Ponts et Chaussées, p. 309 (in French).
2. Rossi P, Acker P, Malier Y (1987) Effect of steel fibers at two different stages: the material and the structures. Materials and Structures. 20: 436-439.

Citation: Pierre Rossi*. True Compression Behavior of Concretes and Fiber Reinforced Concretes. Cur Trends Civil & Struct Eng. 10(2): 2023. CTCSE.MS.ID.000731. DOI: 10.33552/CTCSE.2023.10.000731.

3. Torrenti JM, Benaija EH, Boulay C (1993) Influence of Boundary Conditions on Strain Softening in Concrete Compression Test. Journal of Engineering Mechanics. 119(12).
4. Bazant ZP, Oh BH (1983) Crack band theory for fracture of concrete, Matériaux Constr. 16: 155-177.
5. Mazars J (1984) Application de la mécanique de l'endommagement au comportement non- linéaire et la rupture du béton de structure, Ph.D. thesis, L.M.T (in french).
6. Rots J, Nauta P, Kuster G, Blaauwendraad J (1985) Smeared crack approach and fracture localization in concrete, HERON 30(1).
7. Pijaudier-Cabot G, Bazant Z P (1987) Nonlocal damage theory. J Engrg Mech ASCE 113: 1512-1533.
8. Jirasek M, Zimmermann T (1998) Rotating crack model with transition to scalar damage. Journal of engineering mechanics 124(3): 277-284.
9. Bazant Z, Jirasek M (2002) Nonlocal integral formulations of plasticity and damage: survey of progress. J Eng Mech 128: 1119-1149.
10. Oliver J, Huespe AE, Samaniego E, Chaves E (2004) Continuum approach to the numerical simulation of material failure in concrete, international journal for numerical and analytical methods in geomechanics 28(7-8): 609-632.
11. Oliver J, Huespe AE (2004) Continuum approach to material failure in strong discontinuity settings. Computer methods in applied mechanics and engineering 193(30-32): 3195-3220.
12. Jirasek M (2011) Damage and smeared crack models. In: G Hofstetter, G Meschke (Eds.), Numerical modeling of concrete cracking, Springer, pp.1-49.
13. Hillerborg A, Modéer M, Petersson PE (1976) Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cement and concrete research 6: 773-781.
14. Hillerborg A (1980) Analysis of fracture by means of the fictitious crack model. particularly for fiber reinforced concrete. International journal of cement composites 2(4): 177-184.
15. Stang H, Olesen JF, Poulsen PN, Dick-Nielsen L (2007) On the application of cohesive crack modeling in cementitious materials. Materials and Structures, 40: 365–374.
16. Rossi P, Richer S (1987) Numerical modelling of concrete cracking based on a stochastic approach. Mater Struct 20: 334-337.
17. Rossi P, Wu X (1992) Probabilistic Model for Material Behavior Analysis and Appraisement of Concrete Structures. Mag Concrete Res 44 (161): 271–280.
18. Rossi P, Ulm FJ, Hachi F (1996) Compressive Behavior of Concrete: Physical Mechanisms and Modeling. J Eng Mech 122: 1038-1043.
19. Rossi P, Wu X, Le Maou F, Belloc A (1994) Scale effect on concrete in tension. Mater Struct 27: 437-444.
20. Rossi P, Tailhan JL, Daviau-Desnoyers D (2016) Numerical models for designing steel fiber reinforced concrete structures: Why and which ones? In: Massicotte B, Charron JP, Plizzari G, Mobasher B (Eds.) FRC 2014: ACI-fib International Workshop. FIB Bulletin 79—ACI SP-310, American Concrete Institute: Farmington Hills, MI, USA 310: 289-300.
21. Rossi P, Daviau-Desnoyers D, Tailhan JL (2018) Probabilistic Numerical Model of Ultra- High-Performance Fiber Reinforced Concrete (UHPRFC) Cracking Process, Cement and Concrete Composites 90: 119-125.
22. Rossi P (2023) Numerical Designing of Fiber Reinforced Concrete Eco-Constructions. Materials 16: 2576.

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