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Splitting and crushing failure in FRC elements subjected to a high concentrated load

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ABSTRACT

The local splitting behaviour in Fibre Reinforced Concrete (FRC) elements under a high concentrated load is gaining a growing interest, especially with reference to precast tunnel segments. In fact, during the lining construction process, high concentrated thrust jack forces are introduced in the segments leading to both high compressive stresses under the thrust shoes that can provoke a concrete crushing and tensile transversal stresses that can cause cracks and, eventually, a splitting failure. In order to investigate the main involved mechanisms during either splitting or crushing failure, a simplified analytical study is firstly presented on the two load configurations generally adopted in practice, namely the Line Load (LL) and the Point Load (PL). Based on this analytical study, experimental tests on Steel Fibre Reinforced Concrete (SFRC) specimens subjected to a LL configuration have been carried out. Two different steel fibre types have been studied. Experimental results indicate that the use of a low amount of fibres significantly enhances both the splitting bearing capacity and the ductility. Fibres allow a stable propagation of the splitting crack both in terms of crack opening and development, as a result of a transverse stress redistribution that continuously provide equilibrium with the external applied load.

1. Introduction

A topic of great interest within the international scientific community is the local behaviour of Fibre Reinforced Concrete (FRC) elements subjected to a high concentrated load, mainly regarding precast tunnel lining segments. In fact, during the lining construction process, after assembly a complete ring, the Tunnel Boring Machine (TBM) moves forward by pushing the thrust jacks on the bearing pads of the latest assembled ring (TBM thrust phase); therefore, high concentrated forces are introduced in the back lining which generate high stresses in the concrete under the thrust shoes, i.e. local splitting behaviour. In fact, the diffusion of these forces into the segments leads to a disturbed region (D-region) that has to be carefully analysed, as transverse tensile stresses (defined as splitting or bursting stresses) occur perpendicular to the loading direction, requiring specific local reinforcement generally provided by rebars. The increasing use of FRC in precast tunnel segments [1–4] requires more detailed information (both for the bearing capacity and the crack development) about the local splitting phenomenon in presence of fibre reinforcement only.

One of the first studies on the local splitting behaviour of FRC elements was carried out by Schnütgen [5]; more recently, Tiberti et al. [6] have demonstrated that post-cracking residual strength exhibited by FRC enables a progressive stable development of splitting cracks, which guarantees the increase of the applied load after cracking. Similar tendencies were found in other research works [7,8]. Even though these studies can be certainly considered a good advancement for knowledge on the splitting behaviour of FRC elements, there is still disagreement within the research community on how to study the local splitting behaviour. In fact, the loads can be applied on a loading strip [5,6] resulting in a two-dimensional stress-state condition under the loading areas or they can be further concentrated on a small square areas in order to induce a three-dimensional stress flow [5–8]. Furthermore, the height of the specimen with respect to the expected size of the D-region is another key factor, since FRC will behave as a diffuse tie. The necessary specimen height to properly investigate the progressive propagation of the splitting crack (which allows a new stress distribution) is still a matter of discussion.

In spite of typical relationships suggested by recommendations for evaluating the conventional steel rebars (local steel ties) required as splitting reinforcement [9–13], analytical or semi-

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List of symbols

a	width of loading area
CMOD	crack mouth opening displacement
d	square cross section side of specimen
f_{ck}	characteristic value of the cylindrical compressive concrete strength
f_c	cylindrical compressive concrete strength
f_{cm}	mean value of the cylindrical compressive concrete strength
f_{ct}	tensile concrete strength
f_{Lm}	mean value of the limit of proportionality
f_p	confined compressive strength of concrete
$f_{p,b}$	peak strength of concrete subjected to biaxial compression
$f_{p,t}$	peak strength of concrete subjected to triaxial compression
$f_{R,jm}$	mean value of the residual flexural tensile strength corresponding to CMOD=CMODj
h	height of specimen
$L_{splitting,crack}$	splitting crack depth from top surface at $P_{splitting,crack}$
L_{max}	splitting crack depth from top surface at $P_{\max}$
P	external applied load
$P_{crushing}$	crushing load
P_{max}	maximum load
$P_{splitting,crack}$	splitting crack load
R_{ck}	characteristic value of the cubic compressive concrete strength
R_{cm}	mean value of the cubic compressive concrete strength
V_f	fibre volume fraction
w_{H1}	splitting crack opening from H1
$w_{H1,max}$	splitting crack opening from H1 at $P_{\max}$
$\sigma_{c,max}$	maximum value of the compressive stress under the loading area
$\sigma_{c,splitting}$	compressive stress under the loading area at $P_{splitting,crack}$
σ_0	uniform compression out of the disturbed region
σ_c	compressive stress under the loading area
σ_y	transverse stresses (perpendicular to the loading direction)
$\sigma^+_{y,max}$	maximum transverse tensile stress (perpendicular to the loading direction)
$\sigma^-_{y,max}$	maximum transverse compressive stress (perpendicular to the loading direction)
η	fibre orientation factor

empirical well known relationships are still not available for predicting the bearing capacity, as well as the expected splitting crack width in FRC elements. Schnütgen [5] proposed a simplified analytical approach based on a constant distribution of post-cracking FRC strengths along the splitting crack plane, which is similarly to that currently included in DAfStb [13]. Nevertheless, in these methods, the splitting crack depth is arbitrarily assumed equal to the element side.

It should be considered that, when using FRC structural elements, fibre orientation (with respect to the expected crack surface) in the concrete matrix considerably influence the structural response [14,15]. The latter depends on several factors such as concrete pouring, the geometry of the formwork, the type of vibration and the production method. When steel fibres are used (Steel Fibre Reinforced Concrete, SFRC), relatively economic methods for measuring the average fibre orientation are already available [16–19]. Nevertheless, only few studies, mainly concerning the structural behaviour of FRC tunnel segments during TBM operations, have considered the effect of fibre orientation on the aforementioned local splitting behaviour [17,20,21].

Within this framework, the aim of the present work is to shed a new light on the local behaviour of FRC under a high concentrated load with particular reference to the local concrete crushing or the splitting crack development. To this aim, concrete prisms reinforced by two different fibre types were tested under a high concentrated load. The geometry of the specimens was properly designed by means of a simplified analytical procedure in order to exploit the expected fibre beneficial effects after initial splitting cracking. The proposed method also enables to provide general useful information regarding the main mechanisms as well as the a/d ranges in which either splitting or crushing failures occur. The average fibre orientation factor with reference to the splitting crack plane was also measured by means of the image analysis procedure in order to provide further useful information, which are fundamental for developing advanced non-linear numerical analyses as well as analytical approaches. For this purpose, fibre orientation was also similarly investigated for notched specimens used for determining typical nominal flexural post-cracking FRC residual strengths. The latter are in fact commonly reference fracture parameters widely used for structural design.

2. Splitting behaviour in FRC elements

Two different load configurations are generally adopted for experimentally investigating the local splitting behaviour of FRC elements: line load (LL) [5,6] and point load (PL) [5–7]. A LL configuration (Fig. 1a), which is characterized by a symmetrical axial load applied on a rectangular strip (loading strip width, a Fig. 1a), induces to a two dimensional problem. To the contrary, PL one (square area with side, a Fig. 1b) is subjected to central load which leads to a three dimensional distribution of stresses. Square section (section side length d) is generally adopted for both LL and PL configuration [5–7].

Different values of a/d were adopted so far by authors: 0.11 [7], 0.25 [7], 0.40 [6], 0.43 [5], 0.44 [7]. No authors have motived their choice of using a specific a/d ratio in their experimental tests.

This section reports a simplified analytical study on prismatic elements subjected to LL and PL configurations in order to define the better a/d ratios to be adopted in studying the local splitting behaviour of FRCs and to underline the main differences between these two load configurations.

2.1. Theoretical capacities of prismatic elements under either LL or PL configuration

Two possible failure modes can be observed in a FRC prismatic element under either LL or PL configuration:

- splitting failure, which is due to the transverse tensile stresses depends on the post-cracking response of FRC and occurs at a load level ($P_{\max}$) greater than the external concentrated load at which the cracking for splitting occurs. The latter is called splitting crack load ($P_{splitting,crack}$) and it takes place when the maximum transverse tensile stress ($\sigma^+_{y,max}$) reaches the tensile