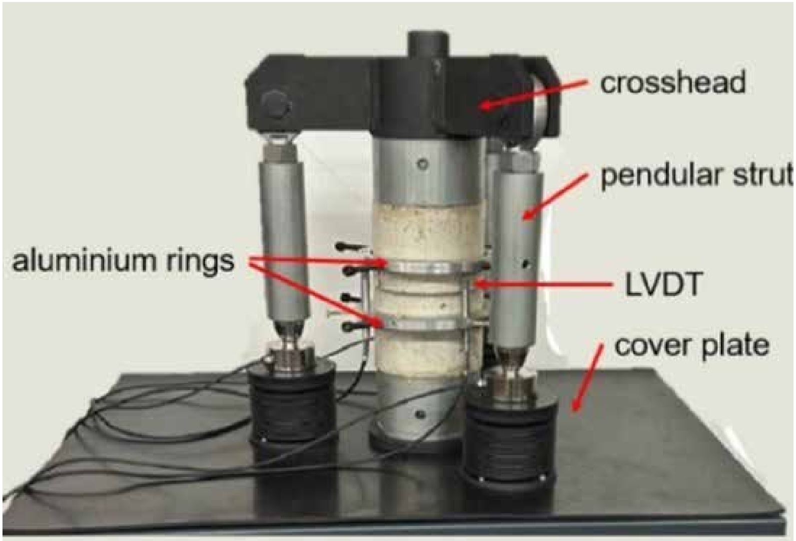
ACI Italy Chapter - Federbeton Awards

INNOVATION IN CONCRETE STRUCTURES AND CEMENTITIOUS MATERIALS – 2024



NBSC 2024, Roma, September 19-20, 2024

Summaries of the PhD Dissertations defended in Italy in the academic years 2021-22, 2022-23 and 2023-24

Editors
Luigi Coppola and Pietro G. Gambarova

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Innovation in Concrete Structures and Cementitious Materials

September 19 -20, 2024 – NBSC 2024, Roma

ACI – Italy Chapter - Federbeton

New Boundaries of Structural Concrete 2024
University of Tor Vergata - Roma
NBSC 2024

If at first you don’t succeed, try, try again

(William Edward Hickson, British educational writer, 1803-1870)

Life is like riding a bicycle: to keep your balance, you must keep moving

(Albert Einstein, 1879-1955)

For those to whom much is given, much is required

(The Bible)

Front photograph from the thesis “Fracture instability in heated concrete: a reassessment of the fundamental mechanisms behind explosive spalling” by Ramin Yarmohammadian, Politecnico di Milano.

Foreword

For the fifth time since 2014, Federbeton – the Italian Association of Cement Producers - is offering the PhD graduates three awards in recognition of the best dissertations on cementitious materials, reinforced/prestressed-concrete structures and composite steel-concrete structures, defended in the academic years 2021-22, 2022-23 and 2023-24. As in previous occasions (2014, 2016, 2018 and 2021), ACI-Italy Chapter is in charge of (a) collecting the long summaries of the dissertations; (b) appointing a committee to shortlist the dissertations, to identify the three best and to indicate those worth an honorable mention; and (c) preparing a volume with all the long summaries, which is published in-print and online by Pubblicemento.

As mentioned in the foreword of the previous volumes, one of the major objectives of ACI is to improve the mutual understanding and cooperation among the Construction Industry, the Cement Producers, the Professions and the Academy represented by the Schools of Civil/Building Engineering, Architecture, Chemistry and Materials Science. Publishing this volume with the long abstracts on the occasion of the 7th Workshop "New Boundaries of Structural Concrete – NBSC 2024" organized by ACI Italy Chapter, Roma (19-20 September 2024) helps in meeting the previous objectives.

Before introducing the long summaries, we should remember the challenges our country has been facing since 2021 in the domain of infrastructures, mostly related to European railway corridors. The most outstanding are: the Frejus tunnel and high-speed/high-capacity line between Brescia and Padua along the Turin-Milan-Venice axis (Mediterranean Corridor); the Brenner tunnel aimed at improving the connections between central Europe and Italy (Scandinavian-Mediterranean Corridor); the third Milan-Genua line along the Rotterdam-Saint Gothard-Milan-Genua axis (Rhine-Alps Corridor); and the Napoli-Foggia high-speed/high-capacity line (part of the Scandinavian-Mediterranean Corridor), first modern line linking the western and eastern coasts of southern Italy in on hundred and fifty years! Last but not least, there is the vexing question concerning the construction of the suspended bridge over the Messina Strait between the southern tip of Italy and Sicily, whose construction is planned to start late this year, with the RC foundations of the tall suspension towers.

Outstanding tunnels, bridges, viaducts, tall buildings and plants for the generation of green energy, however, are sprouting in many countries and the largest Italian construction firms are very active and successful on the international stage in securing big contracts. Hence, the perspectives for civil engineers, architects and materials experts are bright, and such a situation should hopefully increase the enrolment of new freshmen in the university courses concerning especially Civil Engineering, something badly needed today! In fact, not only in Italy but especially in Italy the number of graduated civil engineers is falling to dangerously-low levels, and both the Industry and the Professions are urgently requiring fresh forces, all the more because many newly-graduates are attracted by the better economic conditions offered in other countries. This is, however, in contrast with the enrolment in the PhD courses, that has greatly increased in the last few years thanks to the National Recovery and Resilience Plan (PNRR) based on European Next-Generation Funds, and to the raising interest for higher-level education by the Industry, Professions and Public Administration.

For instance, in the last five years (from 2019/20 to 2023/24) the number of the PhD students has increased by 130% at the Politecnico di Milano (PhD Course in Structural Geotechnical and Seismic Engineering), and the fellowships granted by the Ministry of Higher Education are 10 (8 financed by PNRR, 2023/24) compared to the previous 3 (2019/20).

In spite of the new technical-scientific fields covered by PNRR funds, the interest for cementitious materials and R/C-P/C structures is still sizeable, as demonstrated by the twenty dissertations participating to this competition.

The 20 long summaries come from 10 Italian universities (in two cases in cooperation with foreign universities) and fall into four main broad domains:

- innovative cementitious materials and technologies (4 dissertations = 20%): sustainable high-performance concretes; additive manufacturing and 3D printing; cementitious composite materials in the renovation of masonry buildings.

- RC and PC structures (9 dissertations = 45%):
  - strengthening and retrofitting: confinement via fiber-reinforced cementitious composites, including glass fabrics; dissipative connections;
  - testing and modelling: robustness of precast structures; fracture-mechanics approach in FRC member design; pseudo-dynamic tests; long-term prestressing losses in bridge girders; punching-shear strength in FRC slabs; life-cycle performance of RC and PC bridges;
- durability and extreme conditions (3 dissertations = 15%): UHPC structures; thermal spalling due to heat exposure; concrete deterioration in monumental buildings;
- corrosion (4 dissertations = 20%): bridges; prestressed-concrete beams; deformation capacity (of beams); interaction between cracking and long-term corrosion.

As in the past occasions, the summaries were examined by a committee of five members, four from the Academy and one from the Industry. In the list of merit prepared by the committee (as always, a difficult task!), six summaries of the total received either an award or an honorable mention.

In conclusion, ACI-Italy’s Board and the Committee of Examiners do hope that this volume will be appreciated by all people interested in Civil/Building Engineering, Structural Materials, Architecture and – in general – Construction, not only as a “bridge” between the Academy and the Industry or the Professions, but also between the Academy and the Public Administration.

Board of examiners :
Luigino Dezi, Pietro G. Gambarova, Ezio Giuriani, Paola Pola (Federbeton), Paola Scarfato.
Editors of this volume:
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Premessa

Per la quinta volta a partire dal 2014 Federbeton (Associazione dei Produttori di Cemento) offre ai neoDottori degli anni accademici 2021-22, 2022-23 e 2023-24 tre premi per le migliori tesi di dottorato sui conglomerati cementizi e sulle strutture in calcestruzzo armato e precompresso, includendo anche le strutture composite acciaio-calcestruzzo. Come nelle precedenti occasioni del 2014, 2016, 2018 e 2021, il Capitolo Italiano di ACI si è assunto la responsabilità di (a) raccogliere i sommari estesi delle tesi; (b) nominare una commissione per selezionare le tre tesi migliori e quelle meritevoli di menzione; e (c) preparare un volume dei sommari, che viene pubblicato – anche on-line - da Pubblicemento.
Riprendendo le premesse dei volumi precedenti, uno dei più importanti obiettivi di ACI è quello di favorire la comprensione reciproca e la cooperazione fra l'Industria delle Costruzioni, i Produttori di Cemento, le Professioni e l'Accademia, quest'ultima rappresentata dalle Scuole di Ingegneria Civile/Edile, Architettura, Chimica e Scienza dei Materiali. A tale obiettivo intende contribuire questo volumetto contenente i sommari estesi delle tesi, che viene pubblicato in occasione del 7° Convegno "Le nuove Frontiere del Calcestruzzo Strutturale/New Boundaries of Structural Concrete – NBSC 2024" organizzato da ACI Italy Chapter a Roma (19-20 Settembre 2024).
Prima di introdurre i sommari estesi, è bene ricordare le sfide che il nostro paese sta affrontando dal 2021 nell'ambito delle infrastrutture, con forte presenza dei corridoi ferroviari europei. I progetti più ambiziosi sono: il tunnel del Frejus e la linea ad alta velocità/capacità Brescia-Padova lungo l'asse Torino-Milano-Venezia (Corridoio Mediterraneo); il tunnel del Brennero destinato a migliorare I collegamenti fra l'Europa centrale e l'Italia (Corridoio Scandinavo-Mediterraneo); il terzo valico Milano-Genova lungo l'asse Rotterdam-San Gottardo-Milano-Genova (Corridoio Reno-Alpi); e la linea ad alta velocità/alta capacità Napoli-Foggia (parte del Corridoio Scandinavo-Mediterraneo), prima linea moderna fra le due sponde dell'Italia meridionale in centocinquant'anni! Infine c'è l'annosa e tuttora dibattuta realizzazione del ponte sospeso sullo Stretto di Messina (Corridoio Scandinavo-Mediterraneo), la cui costruzione è prevista a partire dalla fine dell'anno in corso, a cominciare dalle fondazioni in c.a. delle due alte torri sulle coste opposte di Calabria e Sicilia.
Eccezionali gallerie, ponti, viadotti, edifici alti ed impianti per la generazione di energia verde stanno sbocciando in molti paesi, e le maggiori società italiane per le costruzioni sono molto attive – e con successo – sulla scena internazionale, per garantirsi importanti contratti. Le prospettive per Ingegneri Civili, Architetti e esperti di materiali sono quindi favorevoli, e tale situazione dovrebbe sperabilmente portare ad un incremento delle immatricolazioni nei corsi universitari relativi specialmente all'Ingegneria Civile, il ché è oggi assolutamente necessario! Infatti, non solo in Italia, ma specialmente in Italia, il numero di laureati all'anno in Ingegneria Civile sta scendendo a livelli molto bassi, e sia l'Industria che le Professioni sono alla ricerca di forze nuove, tanto più che i neolaureati sono spesso attratti dalle migliori condizioni economiche offerte da paesi con cui competiamo. In contrasto con la tendenza suddetta, la partecipazione ai corsi di dottorato è in notevole aumento, grazie sia al forte impulso dato dal Piano Nazionale di Ripresa e Resilienza – PNRR nell'ambito dei Fondi Europei per la Prossima Generazione, sia al crescente interesse per il Dottorato da parte dell'Industria, delle Professioni e della Pubblica Amministrazione.
Ad esempio, negli ultimi cinque anni (dal 2019/20 al 2023/24), il numero di studenti di dottorato è aumentato del 130% nel Corso di Dottorato in Ingegneria Strutturale, Sismica e Geotecnica del Politecnico di Milano, e le borse di studio assegnate dal Ministero dell'Università e della Ricerca sono 10 (di cui 8 su fondi PNRR, 2023/24) rispetto alle precedenti 3 (2019/20).
Nonostante nuovi campi della ricerca tecnico-scientifica siano stati attivati grazie anche ai fondi del PNRR, l'interesse per i conglomerati cementizi e per le loro strutture rimane elevato, come dimostrano le venti tesi di dottorato in competizione, che provengono da dieci università italiane (con due cooperazioni internazionali) e che riguardano quattro grandi campi:

- compositi cementizi innovativi e relative tecnologie (4 tesi = 20%): calcestruzzi sostenibili ad alte prestazioni; fabbricazione per deposito di strati successivi e stampa tridimensionale; compositi cementizi nel restauro di edifici in muratura;

- strutture in calcestruzzo armato e precompresso (9 tesi = 45%):
  - rinforzo e restauro statico: confinamento per mezzo di compositi cementizi fibro-rinforzati, inclusi i tessuti in fibra di vetro; connessioni dissipative;
  - sperimentazione e modellazione: robustezza delle strutture prefabricate; meccanica della frattura e progettazione di strutture fibrorinforzate; prove pseudo-dinamiche; perdite di precompressione a lungo termine nelle travi da ponte; resistenza al punzonamento di lastre in calcestruzzo fibrorinforzato; vita utile degli impalcati da ponte in c.a. e c.a.p.;
- durabilità e condizioni ambientali estreme (3 tesi = 15%): strutture in calcestruzzo ultraresistente; spacco superficiale del calcestruzzo per esposizione all'incendio; deterioramento del calcestruzzo in edifici monumentali;
- corrosione (4 tesi = 20%): ponti; travi precompresse; duttilità in presenza di corrosione delle armature; interazione fra fessurazione e corrosione.

Sei dei sommari esaminati da una Commissione composta da cinque membri - di cui quattro accademici ed uno industriale - hanno ricevuto un premio od una menzione.
In conclusione, il Consiglio di ACI-Italy Chapter ed i membri della Commissione Giudicatrice sperano vivamente che questo volumetto di sintesi sia apprezzato da tutti gli interessati all'Ingegneria Civile/Edile, ai Materiali Strutturali, all'Architettura ed in generale alle Costruzioni, come "ponte" non solo fra Accademia ed Industria/Professioni, ma anche fra Accademia e Pubblica Amministrazione.

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WINNERS OF FEDERBETON – ACI ITALY CHAPTER’s AWARDS 2024
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Topic A

INNOVATIVE CEMENTITIOUS MATERIALS AND TECHNOLOGIES

INNOVATIVE STRUCTURES OBTAINED WITH DIGITAL FABRICATION TECHNOLOGIES

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Keywords: 3D concrete printing, early-age mortar behaviour, analytical modelling, reinforcement strategy, topological optimization (in 3D printed truss-beams)

1. Introduction

The fabrication of reinforced-concrete structures via 3D Concrete Printing (3DCP) [1, 2] is the subject of this thesis. The 3DCP technology is based on the continuous extrusion of concrete layers or filaments through the nozzles belonging to robotic systems. This technology allows to eliminate costly formworks to produce structural and non-structural members characterized by complex geometries. Other advantages are the reduction of the manufacturing time and the abatement of waste materials. The novelty of this technology, however, brings in many challenges, and among them the definition and characterization of suitable mix designs for printable mortars. In fact, 3D printable mortars must satisfy special requirements: pumpability [3], extrudability [3] and buildability [4]. For such reasons, a comprehensive knowledge of the rheological and mechanical behaviour of printable mortars is necessary to formulate analytical models able to predict the material's response during the fabrication process. Another major challenge is the introduction of the reinforcement during the printing process, which is hardly feasible in the fabrication of structural RC members, to the detriment of the compliance with the building codes. The research activities were divided into three parts focused on different topics: (i) testing and modelling of fresh 3D-printable mortars, (ii) development and testing of reinforcement strategies for 3D printed elements, and (iii) testing of digitally-fabricated and optimized truss-beams.

2. Testing and modelling of fresh 3D printable mortars

An extended experimental campaign based on compression tests performed on fresh-state printable mortars has allowed to propose new testing procedures in the 3DCP field. Specifically, a testing procedure for unconfined uniaxial compression tests (UUCTs) has been proposed (a) to investigate the early-age mechanical behaviour of 3D printable mortars, and (b) to ascertain to what extent their viscous nature may affect the early-age behaviour. The time-dependent relationships of the compressive strength and elastic modulus have been implemented into an analytical model to predict the maximum number of layers that can printed before the collapse of the multi-layer system (due to the compressive failure of the first stacked layer or to the self-buckling of the entire layered system). Furthermore, the calibration of the viscous-elastic Burger model has allowed to satisfactory predict both the instantaneous and delayed vertical strain of cylindrical specimens of fresh mortar subjected to a step-wise loading history with three stress rates (SRs). The test reproduces the stress state of the first layer during the printing process, Figure 1a. The outcomes reported in Figure 1b confirm the efficacy of Burgers' model. The numerical-experimental discrepancy, however, is expected to increase for any loading rate outside the range investigated in this study.

(a)

(b)

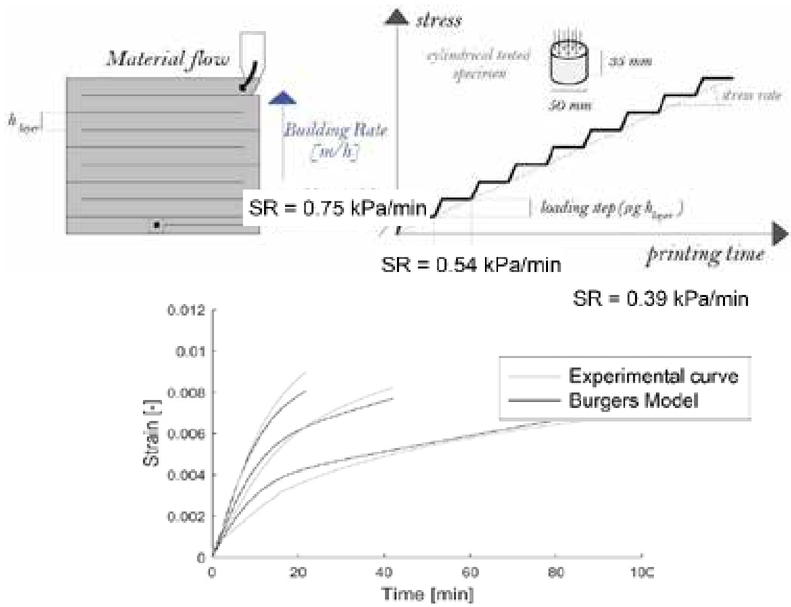

Figure 1. (a) Schematic representation of the stress history acting on the first layer, and (b) experimental vs. theoretical curves from Burgers' model (*RSSsum* = 0.0211).

3. Effectiveness of the reinforcement strategy in 3D printed members

A wide range of reinforcement strategies for digitally-fabricated concrete - DFC has been developed over the recent years [1, 5-7], but in 3DCP, two types of reinforcement are typically adopted: conventional reinforcing bars [8] and flexible filaments [9-10].

(a) **(B)**

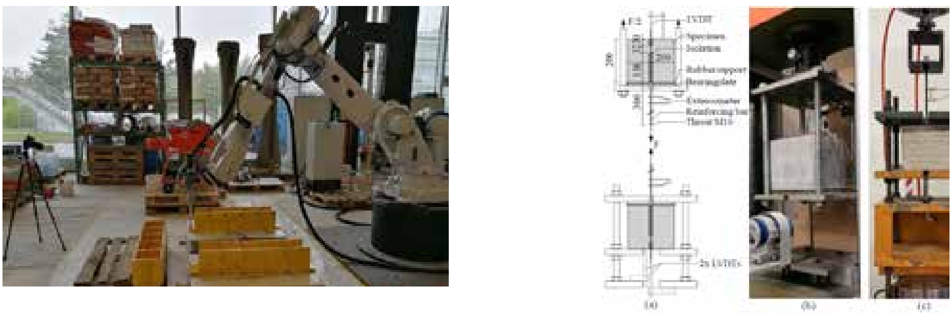

Figure 2. (a) ABB robotic arm printer, and (b) setup for the pull-out tests of printed cubes.

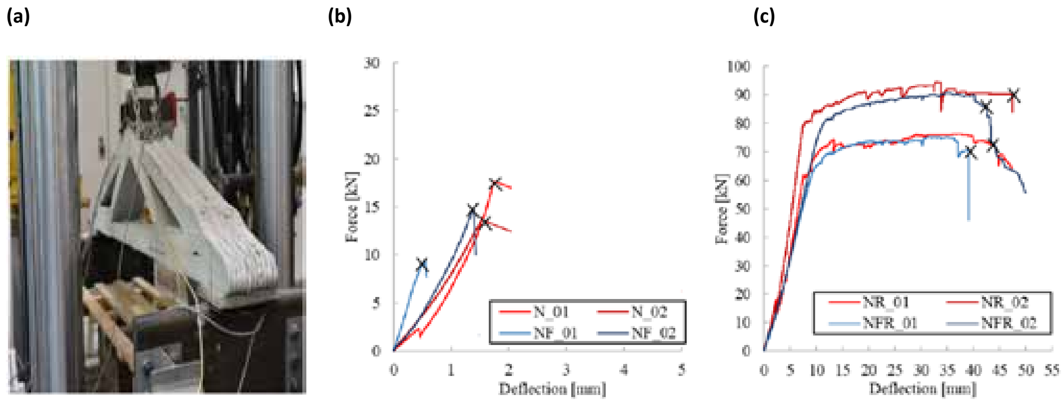

Figure 3. (a) Optimised printed truss-beams before being tested in 3-point bending, (b,c) deflection-force responses of (b) unreinforced and (c) reinforced beams.

An identical experimental campaign has been planned and performed in two different laboratories (University of Naples and ETH Zurich) with the aim to investigate the bond behaviour of steel reinforcement in 3D printed concrete members. Considering the main variables introduced by the 3DCP technology, 30 cubes reinforced with one single steel bar (8 mm) were printed and tested by pulling-out the bar (Fig. 2c), in each institute according to RILEM standards. The experimental results show that the use of reinforcing bars in 3D printing applications can be a reliable strategy as shown by the negligible differences between cast and printed specimens recorded in the tests performed at ETH, and by the reduction close to -20% measured in the tests performed at the University of Naples. This reinforcement strategy was integrated into several printed truss-beams (Fig. 3a). Four reinforced and four unreinforced beams (Fig. 3a) were tested in order to verify the effectiveness of the reinforcement strategy in real-scale structural members. The reinforced truss-beams exhibited a higher bearing capacity and ductility than the unreinforced truss-beams (see Fig. 3c and Fig. 3 b).

4. Concluding remarks

The results of mechanical tests performed on early-age mortar are used in an analytical model for the evaluation of mortar's response during the printing process. The complex nature of fresh thixotropic mortars needs to be considered in the definition of the test parameters (e.g., the strain rate has to be high enough to minimize the hardening during the test, but sufficiently low to avoid viscous strain-rate dependent effects).

Furthermore, the experimental tests performed in this project prove the effectiveness of the reinforcement strategy with steel bars in 3DCP members: the results show that the bond between the reinforcing bars and 3D printable mortars is generally higher than in same-grade conventional concretes. Finally, the proposed reinforcement strategy used in the 3D printing of truss-beams shows that the optimization of the topology brings in a saving close to 25% in both concrete and steel amounts, compared to same-capacity cast truss-beams.

5. Outlook

The technology 3DCP is a novelty, that is bringing digitalization into the construction industry. However, in order to fully exploit the potential of this innovation, it is necessary to overcome the lack in standardization and guidelines. Within this context, scientific collaborations and interlaboratory activities are instrumental in fostering the standardization of the testing procedures and in finding possible solutions face to the many difficulties and challenges typical of any new technology.

Acknowledgements

The financial and industrial support provided by the partner Italcementi (Heidelberg Materials) for the experimental campaign is gratefully acknowledged. The collaborations with the University of Pavia and ETH of Zurich are acknowledged as well, with reference to mortars' properties in the former case, and to the introduction of the reinforcement among the mortar layers in the latter case.

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STRUCTURAL BEHAVIOUR OF EXTRUDED 3D-PRINTED CONCRETE ELEMENTS

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Keywords: 3D-printed concrete (3DPC), hardened properties of 3DPC, interface strength, push-out tests, shear tests, cold joints, modular construction, reinforced/unreinforced 3DPC walls, in-plane cyclic tests.

1. Introduction

Three-dimensional printing of concrete (3DPC) is a modern digital fabrication method characterized by significant economic and environmental advantages, including reduced construction time and costs.
One of the most widely-used fabrication technique for 3DPC elements is by extrusion, which consists of printing through an automated printhead which deposits - layer-by-layer - a filament of fresh concrete. Two approaches are adopted: on-site and off-site fabrication. On-site printing involves creating structures in an open environment, such as the houses printed in Milan (by Italcementi). Off-site printing produces prefabricated elements in laboratory for subsequent on-site assembly such as the bridges in Gemert and Nijmegen both in Netherlands.
While these projects have demonstrated the technology's potential, further scientific research is necessary. Unlike traditional concrete structures, the presence of interfaces (due to the layered structure) can generate a potentially anisotropic behaviour making commonly-used tests (for material characterization of conventional concrete) inadequate. As a consequence, improved methodologies for testing and appropriate guidelines are needed. Furthermore, the properties of 3DPC materials should be controlled in both the fresh [1,2] and hardened state [3,4].
Since the technology of 3DPC is still in its early stages and a common approach to structural engineering still needs to be developed, new design-to-fabrication approaches, test methods and standards are required to allow the use of 3DPC in the fabrication of structural elements. Some structural tests have been carried out recently, such as those on the bridge built in Gemert (The Netherlands) and the large-scale tests performed on 3D printed concrete walls [5].
This research project addresses the previously mentioned gaps, with three main objectives: (a) to propose test methodologies for the assessment of the hardened properties of 3DPC materials, (b) to investigate the structural behaviour of 3DPC walls, and (c) to formulate an analytical model for the description of the structural behaviour of 3DPC walls.

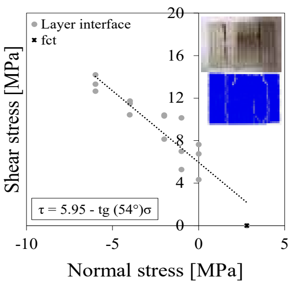
2. Experimental program and analytical models

The hardened properties of 3DPC materials (whose characterization is necessary because materials properties influence the structural behaviour of 3DPC elements) are investigated via a number of tests in compression, tension and bending, considering different orientations for the layers with respect to the applied load [3,4]. Special attention is given to the interface behaviour of 3DPC layers subjected to shear forces. To this end, two test methodologies are proposed by adapting the shear tests typically used for traditional concrete and masonry (Figure 1). The first test is a modification of the *push-out test*, which represents the state of stress of a wall subjected to a transverse in-plane shear force and a vertical compressive load. The second test is a modification of the *slant shear test* with the interfaces subjected to a combined state of shear and compression, in order to obtain the properties of the

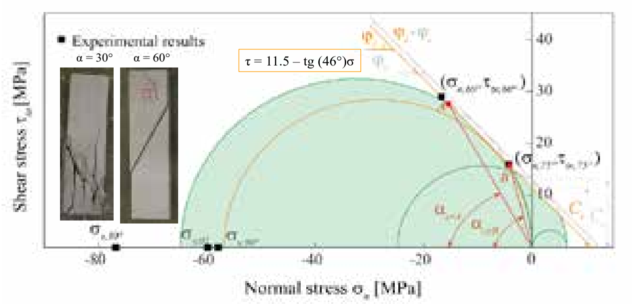
material for different inclinations of the layers with respect to the horizontal printing plane.
On a large scale, the structural behaviour of 3DPC walls is investigated with reference to an off-site printing process employed in the construction of low-rise buildings with modular structural elements. The purpose is first to highlight the main mechanical, geometrical and thermal parameters considered in wall design. The capacity of the wall to withstand lateral loads is experimentally investigated through in-plane quasi-static cyclic tests on full-scale 3DPC walls. One unreinforced and one reinforced wall with vertical steel bars placed in grouted pockets are tested. The reinforced wall also has a cold-joint due to the interruption of the printing process for about 45 minutes due to overheating problems. The walls are subjected to a top cyclic displacement of increasing amplitude and to a constant vertical load representing the load acting on a wall of a two-story building.
Based on the experimental results, an analytical model for the prediction of the structural behaviour of 3DPC walls is proposed (Figure 3).

3. Results

Regarding the hardened properties of 3DPC materials, based on the results of compression, flexure and tensile tests carried out on the 3DPC specimens, what clearly stands out is that the mechanical properties are influenced by the direction of the applied load with respect to the direction of the printed layers. Additionally, the results of the push-out and slant shear tests show how the inclination of the layers can influence the failure mode: the specimens subjected to push-out tests fail only at the interface (Figure 1a), while the specimens subjected to slant shear tests fail due to both interface failure and concrete-matrix failure (Figure 1b), depending on the inclination of the concrete layers. The results of the tests provide valuable insights into shear properties, including shear strength, shear stiffness, cohesion and angle of friction (Figure 1). Together with the strength in compression and tension, the above-mentioned parameters are instrumental in the definition of Mohr's envelope taking into account the anisotropy of 3DPC materials (Figure 1b).



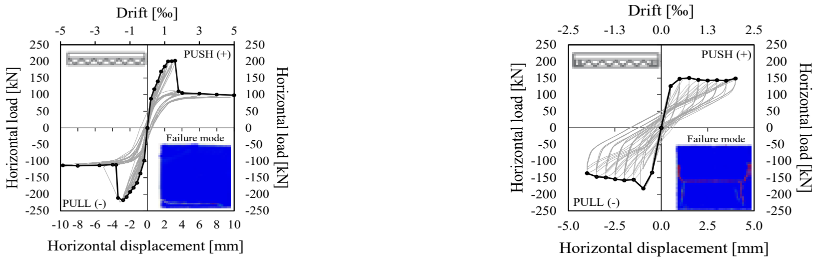
(a)



(b)

Figure 1. Shear properties of 3DPC materials: (a) push-out test; and (b) slant shear test.

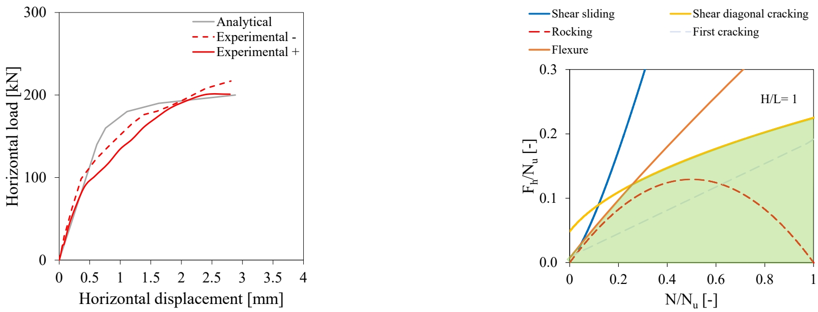
The unreinforced wall (Figure 2a) shows a good lateral response, but the lack of reinforcement makes it brittle in bending, with the formation of a main crack at the base of the wall (Figure 2a). The rocking mechanism governs the post-peak behaviour. The reinforced wall (Figure 2b) exhibits a linearly-elastic behaviour similar to that of the unreinforced wall prior to a premature collapse (compared to the unreinforced wall) due to shear-sliding failure along the cold joint (Figure 2b). This is a specific aspect of 3D-printed structural elements, as cold joints may occur during an in-situ printing process, whenever the printing process is stopped for a long spell.



(a) (b)

Figure 2. Lateral force vs. top displacement of 3DPC walls: (a) unreinf. and (b) reinf. wall.

Based on the mechanical characterization of 3D printed materials, a simple analytical model is proposed to predict the initial stiffness and flexural strength of 3DPC unreinforced walls (the analytical prediction does not include so far reinforced walls). To derive the analytical force-displacement curve (Figure 3a), different contributions are considered, including the flexural deformation, the shear deformation, and the sliding between the layers (determined by means of push-out test).
The model shows the significant role that the redistribution of the tensile stresses after first cracking may have on the wall strength, as well as the influence that the shear behaviour along the interface of the layers may have on wall stiffness. In addition, based on the failure modes of unreinforced masonry structures [6], the interaction diagram of the unreinforced 3DPC wall is derived to investigate how the failure mode changes with the increase of the vertical load applied on the wall (Figure 3b).



(a) **(b)**

Figure 3. 3DPC unreinf. wall: (a) force vs. displacement curves; and (b) interaction diagram.

4. Concluding remarks and outlook

Three-dimensional printing of concrete is a promising digital fabrication technique with significant economic and environmental benefits. Test methodologies for the assessment of the hardened properties of the 3D printed concrete are proposed in this research project, enabling to successfully measure the compressive, flexural, tensile and shear strength. In addition, in-plane quasi-static cyclic tests have been performed on 3DPC walls, and an analytical model has been proposed as well, to evaluate the structural performance of these walls. The results are a small – but hopefully a valuable - contribution toward the definition of common approaches and guidelines for the evaluation of the mechanical and structural properties of 3DPC elements.
Issues such as: (a) push-out vs. slant-shear tests, (b) effect of time gaps (in the deposition of the layers),

(c) arrangement of the reinforcement in 3DPC walls, and (d) strategies to guarantee the efficiency of cold joints are still open to investigation.

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INNOVATIVE AND SUSTAINABLE COMPOSITE MATERIALS FOR THE INTEGRATED RENOVATION OF EXISTING MASONRY BUILDINGS

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Keywords: integrated seismic and hygrometric renovation, masonry buildings, composite materials, fabric-reinforced lime matrices (FRLMs), cork granules (in lime and cementitious mixtures)

1. Introduction

A new composite material – a fabric-reinforced lime matrix (FRLM) - is investigated in order to assess its effectiveness in mitigating the seismic vulnerability of masonry buildings and in guaranteeing the energy efficiency principles required by upgrading.
The mechanical and hygrometric properties of FRLMs are studied as well. FRLMs consist in a basalt fabric embedded in an inorganic natural hydraulic lime-based matrix, with the addition of natural aggregates [1] and specifically of cork granules in this research project. The mix design of a FRLM composite is also proposed for the strengthening of masonry buildings.

2. Experimental program

In the first phase of the project, various commercial insulating thermal plasters, to be used as the matrix of FRLM composites, were selected with the following properties: natural hydraulic lime (NHL) as a binder; natural, recycled or recyclable light aggregates (following the EN ISO 14021:2021 [2]); compressive strength, thermal conductivity and capillarity, like those defined in the standard UNI EN 998-1:2016 [3]. Later, eleven thermal plasters were identified based on their performance in terms of best properties, i.e. compressive strength not lower than 1.50 N/mm^2, thermal conductivity not exceeding 0.1 W/mK and water absorption by capillarity not higher than 0.4 $kg/(m^2min^{1/2})$.
Numerical hygrothermal simulations were performed under different scenarios, applying the selected products to various masonry buildings commonly found in Florence. Additionally, energy simulations at the building scale allowed to evaluate the potential energy savings of the plasters when applied to masonry walls.
In the second phase of the project, the focus was on the mechanical properties of the chosen FRLM composite materials, all reinforced with basalt fabrics. The tensile strength, the bond strength of the composite applied to clay-brick substrate (obtained through shear tests), and the shear strength (obtained from diagonal-compression tests) were evaluated by testing seven masonry panels (one unreinforced panel + three panels reinforced on one side + three panels reinforced on both sides) [4] .
In the third and last phase of this research project, six mixes (Table 1) were prepared using a commercially-available product, indicated as CM (a breathable plaster made of pure NHL, river sand, limestone and pure marble), and six different amounts of cork granules, that are lightweight, biodegradable and recyclable aggregates characterized by low thermal conductivity.

Mixtures	CM [g]	Cork in granules [g]	Mixing water [ml]	Weight pecentage of cork	Volume percentage of cork
Mix 1	100	0	21.24	0.0%	0.0%
Mix 2	100	0.5	21.24	0.5%	4.6%
Mix 3	100	1	21.24	1.0%	5.4%
Mix 4	100	1.5	21.24	1.5%	7.2%
Mix 5	100	2	21.24	2.0%	10.4%
Mix 6	100	3	21.24	3.0%	18.0%

Table 1 - Mix designs of the matrices Mix 1-Mix 6.

To evaluate the workability of the mixes, flow tests were performed, and the segregation of the mixes was checked through X-ray computed tomography [5], which allows a check of the local amount of cork granules through density measurements.

Concerning the cork-modified insulating plasters reinforced with basalt fabric, measurements of water absorption, compressive strength, and adhesion strength to tuff and clay brick surfaces were performed according to ASTM C1403 − 22a [6], ASTM C109/C109M-21[7], and ASTM C1583/C1583M – 20 [8], respectively. In the pull-off tests carried out to evaluate the adhesion strength, the clay bricks with a smooth surface and the superimposed matrix were subjected to detachment at their interface, a fact that required the use of an optical profilometer (according to ISO 25178-2:2021 [9]) to quantify the surface roughness of both the clay and tuff bricks.

3. Experimental results

Among the eleven plasters examined in the first phase, two exhibited the best mechanical properties and low vapor permeability, which contributed to the reduction of the water content and of the moisture-related damage. Likewise, the use of these plasters improved the energy efficiency of the masonry buildings, by reducing the heat loss and decreasing the energy consumption in winter time. Consequently, these two insulating plasters were considered as the most suitable for FRLM composites, meeting both mechanical and hygrothermal criteria.

In the second phase of the study, the direct tensile tests on the FRLM composites (based on the two above-mentioned best matrices reinforced with basalt fabrics) confirmed their excellent mechanical performance. These two composite materials were applied on clay-brick supports, and single shear tests were carried out on three specimens for each type of FRLM, with different bonded lengths (100 mm and 220 mm). One specimen exhibited a brittle behaviour during the test, and its adhesion strength was incompatible with the other specimen, whose behaviour was regular and exhibited a lower tendency to interface detachment. Later, single shear tests were performed on brick masonry columns reinforced with the two FRLM previously-mentioned composites, with a bonded length equal to 290 mm. In the two cases the values of the adhesion strength were very close and approximately more than three times higher than those obtained from single shear tests on individual reinforced brick elements.

From the diagonal compression tests, the best plaster was selected as the reinforcement of the panels. The increase in peak resistance of the reinforced panels compared to the unreinforced ones indicates a significant improvement in structural performance. Specifically, the panels reinforced on both sides exhibited the highest resistance, suggesting that the arrangement of the reinforcement on both faces contributes to an even distribution of the forces across the wall.

In the third part of this research project, the checks on the possible segregation of cork granules confirmed their uniform distribution in the mixes. The flow tests showed the larger the cork volume, the lesser the workability, still within ASTM limits [10].

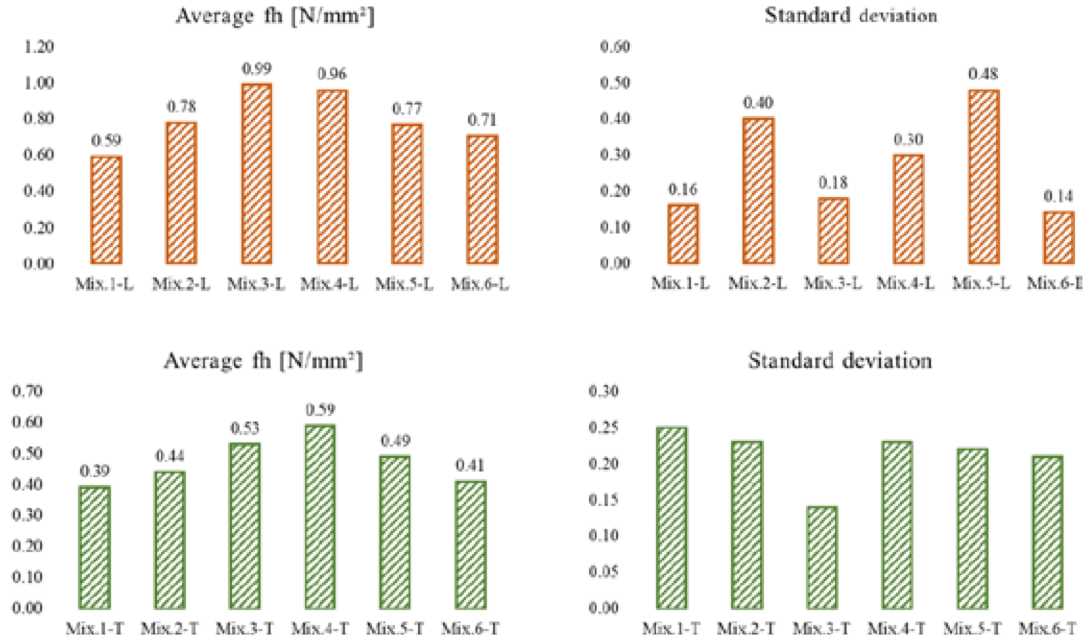

Figure 1. Results of the pull-off tests in terms of average adhesion strength f_h and standard deviation of clay bricks (Mix1 - Mix6 L) and tuff bricks (Mix1 - Mix6 T), where “L” and “T” stand for “clay” and “tuff”, respectively.

The capillary water-absorption tests indicate that the mixes fall within the specified limits, meeting category W1 [3]. The compression tests confirm acceptable strengths, with values never lower than 1.5 N/mm^2. The pull-off tests show a strong dispersion of the results in terms of average adhesion strength f_h [N/mm^2], depending on the difference in the surface roughness of the brick support, that has been analyzed using an optical profilometer [11] and is a key aspect for the bond strength of the composite material.

4. Concluding remarks and outlook

The mechanical and physical tests performed on the innovative FRLM composite proposed in this research project – including the adhesion tests on brick masonry – show that this composite looks promising for the reduction of the seismic vulnerability of existing masonry buildings, as well as for energy saving and sustainability.
Further analyses, however, are necessary in order to put on a solid basis the implementation of the proposed solutions in the integrated requalification of existing masonry buildings.
Because of the critical importance of long-term performance and resilience, additional efforts should be devoted to the assessment of the durability of the proposed FRLM composite under different environmental conditions and aging processes.

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DESIGN ISSUES AND MECHANICAL-STRUCTURAL CHARACTERIZATION OF SUSTAINABLE HIGH-PERFORMANCE CONCRETES

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Keywords: sustainable concretes, cement-less concretes, alkali-activated binders, bond-slip behavior, steel and FRP bars, real-scale tests, ultra high-performance fiber-reinforced concrete – UHPFRC, synthetic fibers, toughness, impact tests, FEM analysis

1. Introduction

The recent trends in concrete technology have led – and are still leading - to the development of innovative – and even new - materials in order to meet today's urgent environmental and economic necessities. Due to its low cost and ease of production, concrete has become the most widely used construction material, with serious and harmful consequences on the planet and human health because of the large amount of carbon dioxide produced by the cement industry, the continuous demand for natural resources such as water and aggregates, the significant cost of repair and maintenance, and the increasing demolition-related waste generation [1].
In particular, the need to reduce carbon-dioxide emissions has paved the way to the increasing use of the geopolymer binders as a valid alternative to ordinary Portland cement [2-4]. On the other hand, the research for more durable and long-lasting structures – with reduced or even zero maintenance costs – are favoring the use of ultra high-performance concretes (UHPCs) generally containing short fibers [5-7]. The present research is focused on these two new concrete technologies, that deal with two different aspects of the same *green* philosophy (concrete sustainability): how to make concrete *cement free* and to give it a *high/ultra high performance*.

2. Experimental program and analytical models

As regards geopolymer concrete, the aim of this work is to improve the knowledge about its use in structural applications. An extended experimental campaign has been carried out on two cement-free geopolymer concrete mixes. In particular, the mechanical properties such as the compressive strength and the modulus of elasticity have been investigated together with bond with both steel and fiber-reinforced polymeric (FRP) bars. The experimental data obtained from the pull-out tests have been elaborated and discussed in depth in terms of stress transfer mechanisms, mode of failure, and bond stress versus slip law. Moreover, several bond parameters such as the diameter, the bonded length and the quality of bar surface have been analyzed in order to assess the influence of the various variables. Finally, the structural behavior of the geopolymer concrete mixes has been studied. Three real-scale beam-like specimens were cast and tested. A geopolymer binder was used in the mixes of the first two beams, while the mix of the third beam contained ordinary Portland cement. Four-points bending tests were performed on the beams and the results were compared in

terms of flexural behavior (failure load, deflections and deformations in the midspan section) and crack pattern (crack number, depth and width).
A parallel research project on ultra high-performance fiber-reinforced concrete (UHPFRC) was focused on the influence of synthetic fibers on concrete with elevated mechanical properties. Based on the same UHPC mix, three UHPFRC mixes were prepared containing PVA (polyvinyl-alcohol) microfibers or PP (polypropylene) macrofibers or a mix of both types, and a fourth *reference* mix was had no fibers. These concretes were tested both at the fresh and after hardening. The post-hardening characterization included tests on the compressive and tensile strengths, modulus of elasticity, stress-strain laws, toughness (via 3- and 4-point bending tests) and water permeability. The role of the synthetic fibers was deeply investigated by analyzing the post-peak behavior of the bending tests to calculate the fracture energy. The permeability tests were carried out on uncracked cubic specimens in order to measure the water absorption in UHPC mixes with and without fibers. In addition, a thin panel was cast for each of the four mixes to perform impact tests aimed at assessing the contribution of the fibers to the damage in terms of crack pattern, opening of the major cracks and crack density. The same tests were modelled via finite elements (FE), by introducing the properties of the materials yielded by inverse analysis applied to three-point bending tests.

3. Results

Apart from the initial bond stiffness, the bond stress vs. slip curves (maximum bond stress, softening branch and final residual strength) of the ribbed glass-FRP bars (rGFRP) and those of the ribbed steel bars are almost overlapped (Fig.1a). Similarly, the curves of the sanded glass-FRP bars (sGFRP) and those of the sanded carbon-FRP bars (sCFRP) are very close (average bond stress and overall bond stress vs. slip behavior, Fig.1b).

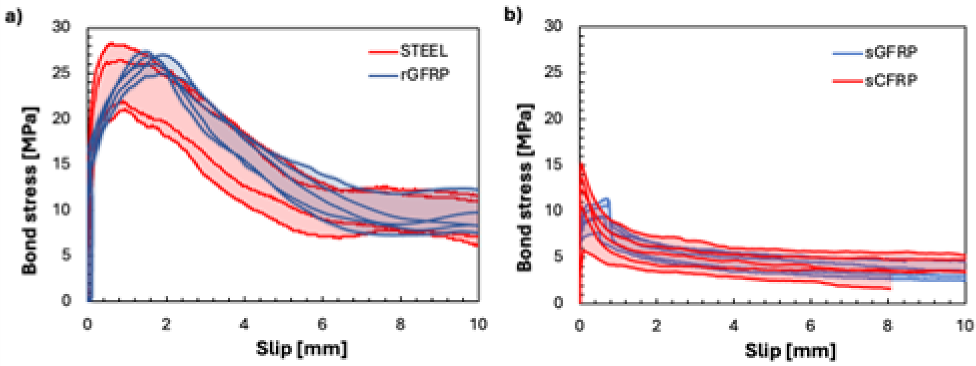

Figure 1. Comparisons between (a) pull-out tests with ribbed steel bars and ribbed GFRP bars (rGFRP bars), and (b) pull-out tests with sanded GFRP and CFRP bars (sGFRP and sCFRP bars).

The moment-curvature curves of the beams made of geopolymer concrete - GPC and ordinary Portland-cement concrete - OPCC are in good agreement with the theoretical curves, confirming the validity of classical assumptions and design also in the case of geopolymer concrete. However, the bending capacity is underestimated for both geopolymer and ordinary concretes. This discrepancy can be attributed to the analytical assumptions made in the design process. The prediction of the crack width made according to the Model Code is conservative with respect to the experimental values measured by means of strain gauges positioned on concrete and steel bars. The approach adopted by the Model Code remains, therefore, valid even in the case of geopolymer binders.

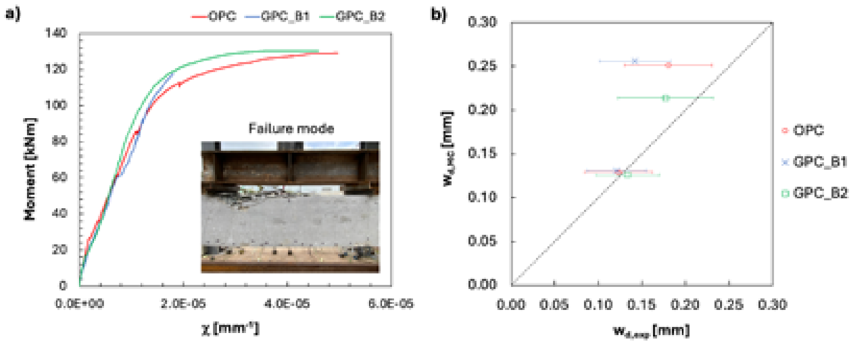

Figure 2. (a) Experimental moment vs. curvature curves, and (b) crack opening according to Model Code 2010 vs. the crack opening measured in the tests.

The bending tests yield interesting information about the influence that the different types of synthetic fibers may have on the toughness of UHPFRC mixes. In fact, once cracking is activated, PVA microfibers make the resistance decay more regular compared to the other mixes. Furthermore, the post-cracking behavior is markedly dependent on fiber type and amount, particularly for high values of the crack mouth opening displacement - CMOD. The mix with PP macrofibers allows the specimens to carry higher loads from the situation with CMOD = 1 mm to the end of the test.

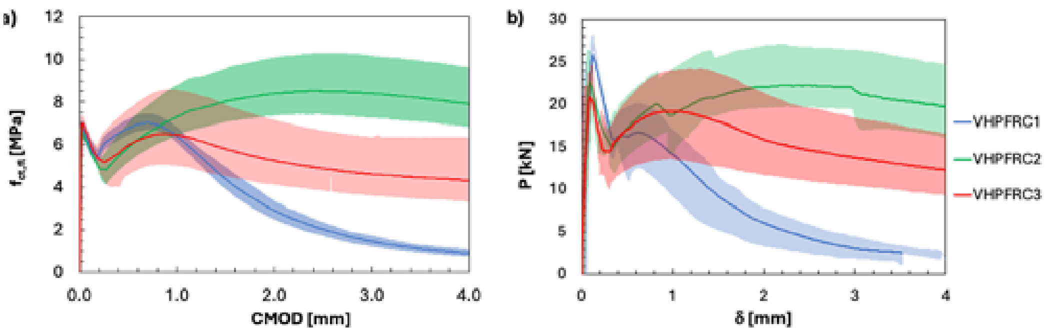

Figure 3. Flexural tests on UHPFRC specimens: (a) 3-point bending tests according to EN 14651, and (b) 4-point bending tests according to ASTM C1609.

Finally, synthetic fibers provide unreinforced thin panels a sizeable impact resistance.
Both PVA microfibers and PP macrofibers play a crucial role in reducing the width of the cracks. PVA microfibers are particularly effective during the stages of crack formation and propagation, with a decrease in both the number and length of the cracks. Synthetic fibers improve also the kinematic behavior of thin plates subjected to impact, as lateral deflections are markedly reduced.

4. Concluding remarks

The innovative concrete technologies used in the experimental campaign and the constitutive relationships based on the test results are a contribution to face the sustainability challenges associated with the production and service life of ordinary concrete, that may be in many cases replaced with more sustainable high-performance and ultra high-performance concretes, with the added advantage of the fibers.

5. Outlook

The long-term behavior (durability and creep) of geopolymer-concrete structures, their structural performance when reinforced with glass fiber-reinforced polymeric bars, and certain specific identification methods based on inverse analysis are among the issues open to further investigation.

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Topic B

R/C AND P/C STRUCTURES
B0 - Strengthening and Retrofitting

B01 **ELEONORA GROSSI** - A novel 2D dissipative connection for the seismic retrofit of precast structures: conceptualization, prototyping, mechanical characterization and numerical modelling

B02 **MARCO CARLO RAMPINI -** Glass fabric-reinforced cementitious composites: strengthening and retrofitting of existing RC structures

B03 **KLAJDI TOSKA -** Innovative techniques for monitoring and strengthening existing structures: fabric-reinforced cementitious composites for the confinement of RC structures

A NOVEL 2D DISSIPATIVE CONNECTION FOR THE SEISMIC RETROFIT OF PRECAST STRUCTURES: CONCEPTUALIZATION, PROTOTYPING, MECHANICAL CHARACTERIZATION AND NUMERICAL MODELLING

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Keywords: precast RC structures, beam-column connections, friction dampers, tribology, cyclic tests, Pin-on-Disk (PoD) tests, bidirectional damping, FEM analysis.

1. Introduction

Precast Reinforced Concrete (RC) structures have been widely used in industrial and commercial buildings since the 60s. However, most of the buildings were constructed with poor detailing and their design was based only on gravity loads. As a result, this structural typology often faces significant seismic risk in earthquake-prone areas, as stressed in the 2000 FIB report [1] and confirmed by the 2012 Emilia Earthquake[2].
The seismic retrofit of precast RC structures is essential to prolong their service life and mitigate seismic losses. The most common solutions involve traditional techniques [3] and passive-control techniques based on energy dissipation [4], but their adoption requires particularly invasive works [5].
The need for better structural connections and less invasive energy-dissipation devices leads to the concept of dissipative connections. Several scholars have developed such connections [6–8], proving their efficiency in terms of energy dissipation and base-shear reduction. However, they are effective only in one direction, hence additional dampers are necessary to ensure isotropic energy dissipation. This is not possible in precast RC structures where the connections of the orthogonal beams to the main frames are little effective. There is, therefore, a need for devices able to improve the seismic performance of buildings even if they lack a 3D structural configuration. This study focuses on the conceptualization, prototyping, mechanical characterization and numerical modelling of a 2D dissipative connection called Bidirectional Rotational Friction Damper (BRFD) for the seismic retrofit of precast RC structures lacking a 3D structural configuration.

2. Conceptualization

The BRFD is obtained by assembling a number of metallic *layered* plates in a movable geometry to achieve a bidirectional behaviour. In Figure 1a an axonometric view of the BRFD is provided, while Figure 1b shows an example of its installation between the beam and the column of a main portal frame, with an inclination of 45°.

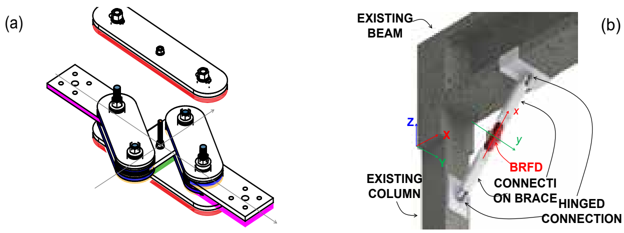

Figure 1. BRFD: (a) axonometric view; and (b) installation in a beam-to-column joint.

The conceptual study has required the development of an analytical model to describe the BRFD behavior using a simplified approach. This analytical model is basically the combination of two components, the first longitudinal (local direction) and the second transversal (local direction). The associated hysteresis cycles are uncoupled and can be described by means of a bilinear hysteretic law.
To evaluate the influence of BRFD on the structural behavior during a seismic event, a case study is presented about a single-story, single-bay precast RC structure devoid of secondary frames, where a BRFD is placed inside the main frame. Quasi-static analysis shows that the BRFD positively influences the structural behavior, without alterations in the top displacement associated with column yielding and with only a slight increase in the related total base shear.
To identify the optimal configuration of the BRFD in the case study, a sensitivity analysis has been carried out by adopting a multi-criteria decision-making (MCDM) approach [9]. The introduction of the optimal BRFD's configuration improves the dynamic performance, and significantly reduces the interstorey drift (-62%) and the total base shear (-28%), without alterations in the existing structural scheme and without structural and non-structural damage.

3. Device prototyping and tribological study

The prototyping of the BRFD consists of a tribological study performed by using Pin-on-Disk (PoD) tests. PoD tests are aimed at creating the real in-service conditions of the device in question, under the action of subsequent earthquakes.
Carrying-out preliminary running-in stages is shown to significantly reduce the transition time necessary to guarantee a steady coefficient of friction. Moreover, the interaction between the steel and softer metals - and especially between nickel-treated steel and bronze - exhibits the best behavior.

4. Mechanical study

In order to investigate the mechanical behavior of the proposed connection under 1D and 2D displacements, experimental tests have been performed following the EN 15129 guidelines, for different frequencies (from 0.05 Hz to 2.00 Hz) and displacement amplitudes (from ± 10 mm to ± 40 mm).
The BRFD prototype was manufactured by considering two different friction interfaces: nickelled steel vs. nickelled steel (NN) and nickelled steel vs. bronze (NB). Three test groups were introduced: Group 1 (G1) aimed at assessing the 1D behavior of the BRFD; Group 2 (G2) aimed at determining the relationship between the coefficient of friction and the velocity; and Group 3 (G3) aimed at assessing the 2D behavior of the BRFD.
The results of G1 and G3 tests show that the hysteresis cycles for NN and NB configurations (Figure 2a,b and 2c,d, respectively) are mainly in both and directions, and have the same signal frequency. This is a promising behavior as it means that the performance of the device during an earthquake remains dependable, regardless of the ground motion frequency content.

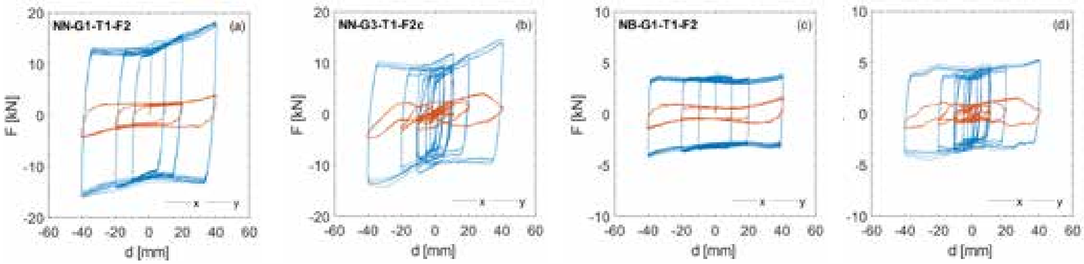

Figure 2. Hysteresis cycles in the and directions of NN for G1 (a) and G3 (b) tests, and of NB for G1 (c) and G3 (d) tests.

G2 test results show that the relationship between the friction coefficient and the sliding velocity decreases when the velocity increases.

The findings of the mechanical investigation show that the bidirectional behavior of the BRFD device is promising, in terms of hysteresis-cycle steadiness and good damping capacity, especially in the case of the NB configuration.

5. Numerical study

The numerical study focuses on the definition of two different friction-based numerical models for BRFD devices: a simple model for an easy implementation inside a frame structure, and a more refined model to be used as a Virtual Lab tool.

The simplified model efficiently reproduces the overall behavior of the BRFD when subjected to a mono-directional sinusoidal displacement law, but the description of the transversal (*y*) component is acceptable only in the case of a 2D waveform orbit.

The refined numerical model efficiently reproduces the overall behavior of the BRFD under both mono-directional displacement laws and 2D waveform orbits. Moreover, the shapes of the hysteresis cycles closely fit those recorded during the mechanical tests (Figure 3), this being a confirmation that their aspect results from a combination of the device's geometrical layout and the 2D waveform of the selected orbits.

6. Concluding remarks

The present work shows that BRFD devices can significantly improve the seismic behavior of precast RC structures by developing steady and reliable hysteresis cycles. Moreover, the proposed friction-based numerical model can be used as a Virtual Lab tool to reproduce (a) the real behaviour of BRFD devices inside an experimental setup, and (b) the real interaction between the devices and the structural systems.

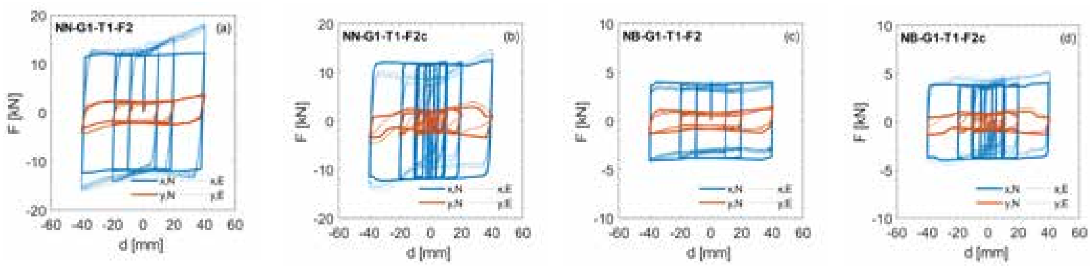

Figure 3. Hysteresis cycles in the and directions of NN for G1 (a) G1 and G3 (b) tests, and of NB for G1 (c) and G3 (d) tests. Comparison between experimental (E) and numerical (N) results.

7. Outlook

In spite of the promising results obtained so far, the proposed approach needs a deeper validation. Furthermore, to investigate the benefits of BRFDs placed in existing buildings, additional numerical studies should be performed by considering different structural layouts, and tests on the shaking table should be carried out on reduced-scale prototypes of precast RC buildings.

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GLASS FABRIC-REINFORCED CEMENTITIOUS COMPOSITES: STRENGTHENING AND RETROFITTING OF EXISTING REINFORCED CONCRETE STRUCTURES

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Keywords: Textile Reinforced Concrete (TRC), Fabric-Reinforced Cementitious Matrix (FRCM), alkali-resistant glass fabric, reinforced-concrete structures, fibre-reinforced structures, flexural retrofitting, shear strengthening, shallow beams, slabs, coupling beams.

1. Introduction

Recent seismic events in Italy have confirmed the vulnerability of many existing buildings. The composites based on fabric-reinforced cementitious matrices (FRCMs) offer a solution for reinforcing and upgrading structural members. Their advantages include compatibility with irregular substrates, ease of application, permeability, fire resistance, and lower installation costs compared to alternatives. Interest in these materials has increased with the introduction of new Italian standards and CRN design guidelines, making it possible for designers to evaluate the performance of such innovative materials and to use FRCMs in structural strengthening. This research project aims at assessing the effectiveness of glass-based FRCM composites in strengthening lightly-reinforced concrete (RC) structures through an extensive experimental campaign, and to develop simplified design equations for both strengthening and retrofitting.

2. Experimental program and modelling

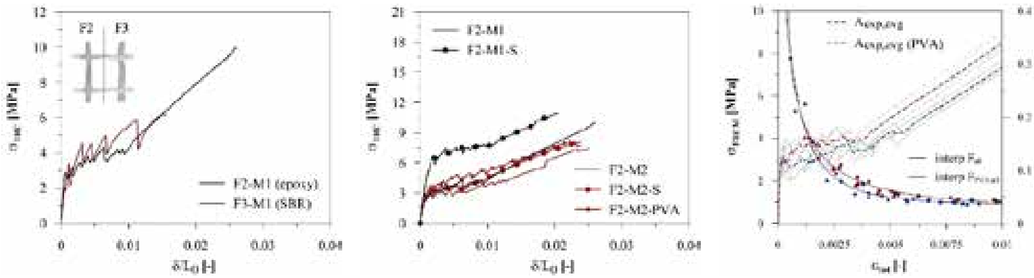
The experimental campaign involves three levels of analysis (Fig. 1):

- characterization of FRCMs in uniaxial tension (under both monotonic and cyclic loading), using different matrices reinforced with alkali-resistant glass fabrics or dispersed short fibres, and optimization of the composites in order to define the material to be used in later steps;
- meso-scale experimentation (in shear on single laps, and in tension via double-edge wedge splitting), with the focus on bond behaviour at the substrate-to-composite interface, and investigation on the role played by the preparation of concrete surfaces;
- execution of monotonic and oligo-cyclic full-scale tests on different structural members under in-plane and out-of-plane actions (beams, slabs and coupling beams) to assess the potential of FRCMs in strengthening and retrofitting.

Figure 1. Representation of the three levels of the analysis: from material to full-scale tests.

3. Results

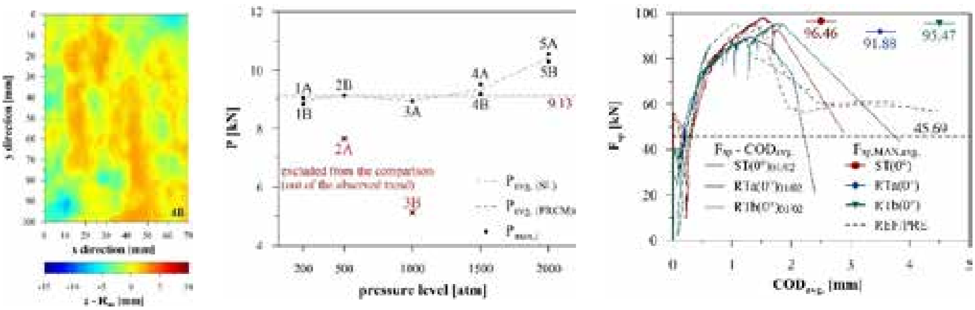
More than 300 monotonic uniaxial tensile tests were performed to optimize the composite: fabric characteristics (quantity of glass, warp and weft geometries, and yarns distribution, nature of the coating), matrix properties (strength, workability, thixotropy, composition, addition of polymers etc.) and type of fibres (steel, PVA, etc.). The comparison was performed in terms of efficiency, energy consumption and extension of the multi-cracking branch [1, 2].



(a) (b) (c)

Figure 2. Effect of the coating and fibres on monotonic (a, b) and cyclic (c) tension behaviour.

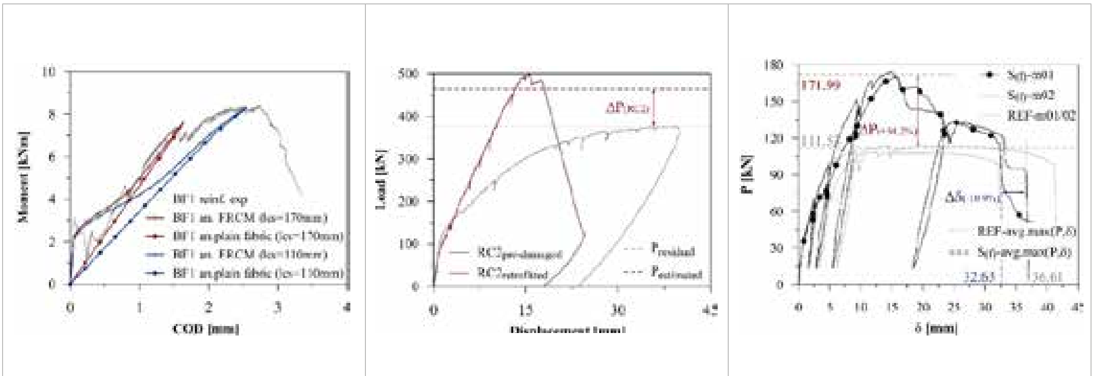
In addition, a series of loading-unloading tests were carried out to examine the effect that PVA short fibres may have on the stiffness degradation of FRCM composites [3]. The results allow to observe that: (a) coating nature and fabric weaving have a significant influence on the global capacity of FRCM, mainly in terms of global efficiency (Fig.2a); (b) adding short fibres increases the mechanical capacity (Fig.2b) and makes the cracks thinner; (c) increasing the thickness of the composite layers may be needed when heavy-duty textiles are used, to better control any internal slip of the fabric, and (d) adding PVA short fibres slightly counterbalances the stiffness degradation of the composite (Fig.2c).
Various concrete substrates were prepared by hydroscarification with water pressures ranging from 200 to 2000 bar (see laser measurements in Fig.3a) before casting FRCM strips. Single-lap capacity was related to surface finishing, a clear sign of the role of machining in improving FRCM performance (Fig. 3b) and in preventing weak failure modes (detachment from the substrate) [4].
Before going on with full-scale tests, the effectiveness of FRCM composite was investigated through Double-Edge Wedge Splitting (DEWS) tests (Fig.3c) [5]. Such tests allowed to check the pre-damage state (crack opening = 0, 0.3 and 1.5 mm) and to analyse the effect of fabric orientation (0° and 45°). The test results from DEWS were confirmed by means of nonlinear numerical analysis and simplified models.



(a) (b) (c)

Figure 3. Substrate after hydroscarification (a), single-lap shear test (b), and double-edge wedge-splitting (DEWS) tests (c).

The results of the out-of-plane tests (Fig.4a-b) carried out on RC/SFRC pre-damaged shallow beams and slabs [6] show that FRCMs seem adequate to restore the capacity and (partially) the stiffness with respect to undamaged members in bending. The performance improvement at serviceability limit state is evident, in parallel with the need to introduce safety coefficients to avoid the occurrence of weak failures. In addition, provided that appropriate assumptions are introduced on crack distance, the moment-crack opening curves of the beams can be realistically re-created within a plane section approach (Fig. 4a).



(a)	(b)	(c)

Figure 4. Full-scale tests: responses of beams (a), slabs (b) and coupling beams (c).

Regarding in-plane actions, a series of RC coupling beams were tested under either monotonic or cyclic loads, for different base materials for FRCMs (polymeric mortars, PVA fibres) and initial conditions (undamaged and pre-damaged beams, with the focus on both strengthening and retrofitting [7].
All the different solutions yield a capacity improvement (as confirmed by the validation via simplified analytical shear models), but only by adding short PVA fibres premature weak shear failures can be prevented, whatever the loading (monotonic, Fig.4c, or cyclic).

4. Concluding remarks

The most important results and the main contribution of this project within the broad field of FRCM composites are: (i) the experimental investigation from the material to the full-scale level, under different actions (out-of/in-plane and monotonic/cyclic loads) and using a significant variety of base materials (mortars, fabrics and short fibres); (ii) the development of an analytical model to predict the trilinear behaviour of FRCMs; (iii) the definition of a stiffness-deterioration law in case of cyclic tests in tension; (iv) the formulation of roughness requirements for the support-composite interface, to fully exploit FRCM potential; (v) the quantification of the effect of fabric orientation; and (vi) the introduction and validation of a simplified analytical approach aimed at describing the response of FRCM-reinforced RC members.

5. Outlook

Further developments include the extension of the experimentation to other structural members and the assessment of FRCM effects on structural durability. Furthermore, coupling nonlinear numerical modelling and testing may make the findings of the present work more general.

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INNOVATIVE TECHNIQUES FOR MONITORING AND STRENGTHENING EXISTING STRUCTURES: FABRIC-REINFORCED CEMENTITIOUS COMPOSITES FOR THE CONFINEMENT OF RC STRUCTURES

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Keywords: cementitious composites, concrete structures, retrofitting, repair, fabric-reinforced cementitious matrices – FRCMs

1. Introduction

Reinforced concrete (RC) structures face significant age-related challenges, including deterioration due to environmental factors, aging, and damage from overloading. These issues require modern retrofitting techniques to guarantee structural safety and compliance with actual code provisions.
In this context, new cementitious composites, such as Fabric-Reinforced Cementitious Matrices (FRCMs) or Textile-Reinforced Mortars (TRMs), are an efficient, compatible and sustainable solution for the retrofitting of existing structures [1]. Among other techniques, rehabilitation of RC elements by means of external jacketing not only increases their axial load bearing capacity but also significantly improves their ductility and therefore the overall seismic performance [2-3]. A significant number of issues, however, remains open to investigation.
Within this context, four experimental campaigns to investigate FRCM's effectiveness in various loading conditions is presented, with the ultimate goal of filling the knowledge gap on the behaviour of repaired and retrofitted members confined by means of FRCM jacketing, and developing a reliable, design-oriented model for FRCM- confined concrete.

2. Experimental Programme

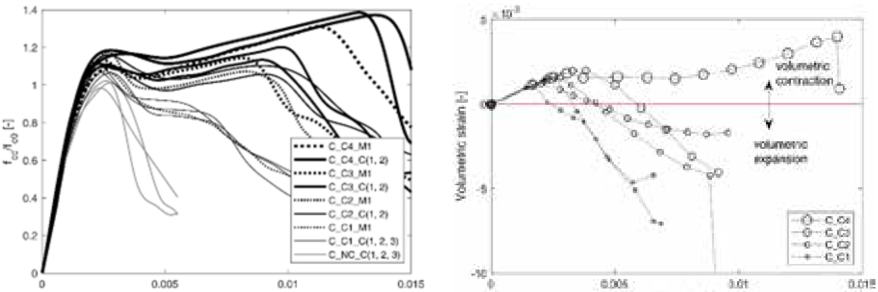
Four are the experimental campaigns carried out during this research work, aimed at investigating the behaviour of FRCM-confined concrete, in terms of:

i. Monotonic and cyclic axial behaviour of FRCM-confined plain concrete; 37 small-scale specimens (h = 300 mm) were tested to investigate the roles of: fibre material (carbon and glass), number of layers (1 to 4), cross-section geometry (circular, square, and rectangular) and loading procedure (monotonic and cyclic).
ii. Confinement effectiveness of FRCM composites on real-scale RC columns; the main investigated variables include cross-section shape (circular with D = 300 mm and square with a x b = 300 x 300 mm) and spacing of the transverse reinforcement.
iii. FRCM confinement as a repair technique for damaged RC columns because of excessive axial loading; damaged RC columns as in campaign (ii) were repaired by means of FRCM jacketing and tested under monotonic axial loading.

iv. Repair of seismically-damaged real-scale RC columns confined by means of FRCMs (under cyclic lateral loading); in the fourth campaign two full scale RC columns (a x b x h = 400 x 400 x 1000 mm) were initially damaged under cyclic lateral loading and later tested again following the same loading procedure, after being repaired by means of FRCM jacketing; the lateral-strain development in the reinforcing fabric was continuously monitored during the loading phase; note that (a) the corners of the square-section columns were rounded before the retrofitting, and (b) the tensile behaviour of the two FRCM systems employed in the experimental campaigns (based on carbon and glass fibres) was investigated prior to testing.

3. Experimental Results

The tests on small scale FRCM-confined concrete specimens confirm the effectiveness of FRCM composites in increasing the axial strength and ductility of retrofitted members. The envelope of the stress-strain curves of cyclically-loaded members does not show any significant difference compared to monotonic curves. Carbon fabrics and cylindrical specimens perform better than glass fabrics and prismatic specimens. The lateral-strain monitoring inside the FRCM jacket allows to analyse the dilatation and the confinement effect on the lateral expansion during the loading phases (Fig. 1b) [4].

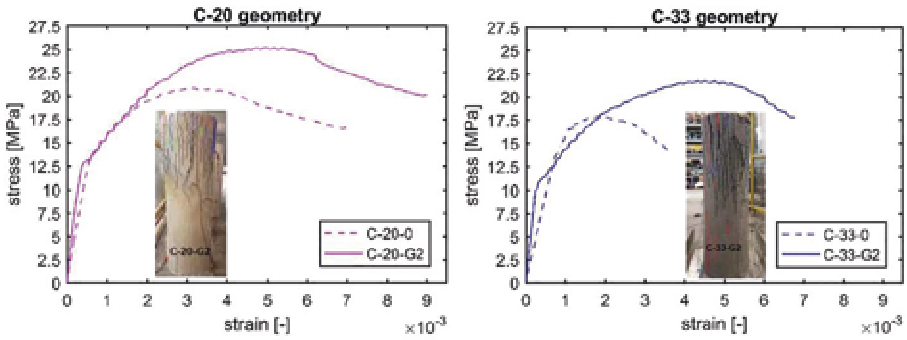


a) b)

Figure 1. Envelope and monotonic stress-strain curves (a), and volumetric vs. axial strain (b).

The application of FRCM confining jackets to real-scale RC columns yields satisfactory results in terms of compressive strength and axial strain capacity. Furthermore, a favourable interaction between the FRCM-jacket and the internal transverse reinforcement is expected to occur [5].

Positive effects were observed also when the FRCM jacket was applied with the aim of



a) b)

Figure 2. Stress-strain curves: 200 mm (left), and 330 mm (right) stirrup spacing.

repairing previously damaged members. With respect to the residual strength of damaged members, the repair can even double (and more) the ultimate capacity of cylindrical columns with densely-spaced stirrups. The effectiveness tends to decrease in prismatic columns and for large stirrup spacings [6]. The lateral strains are higher (a) in damaged columns with respect to undamaged columns, and (b) in the columns characterized by less-effective cross-sections and transverse steel arrangements (Fig. 3b).

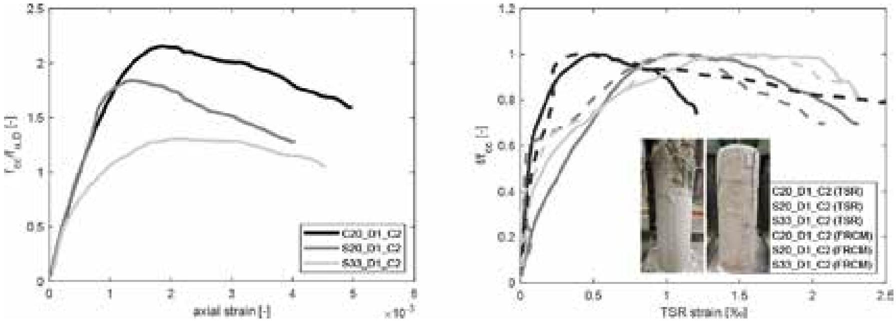
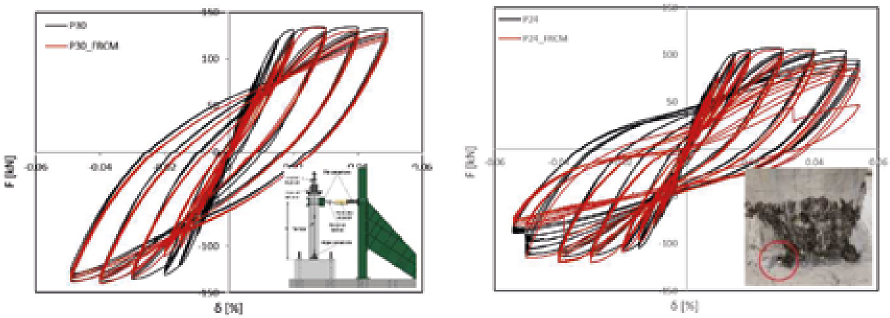


Figure 3. Axial strain vs. the ratio between confined and residual strength (left), and strain development in the stirrups and in the confining jacket (right).

Regarding the seismic performance after jacketing, the experimental results show that FRCM confinement can restore the initial strength and the lateral displacement capacity in seismically-damaged members (Figure 4). Furthermore, the repaired RC columns dissipate almost the same energy as the undamaged ones. The initial stiffness cannot be fully restored unless additional reinforcement is embedded inside the confining jacket [7].



a) b)

Figure 4. Load vs top displacement for reference (black) and FRCM-repaired (red) columns.

4. Analytical model

A new design-oriented stress-strain model for FRCM-confined concrete is proposed based on the experimental results. Three stages of the confinement effectiveness can be recognized based on (a) the ratio between the lateral confining pressure and the unconfined strength (f_l/f_{c0}), and (b) the stress-strain curve obtained from the tests.

Simplified formulations for the stress-strain curves are provided as well. For the sake of simplicity, the strength gain in the first peak (mainly due to matrix stiffness) is neglected. An extensive experimental database collected from recent literature has been used to verify the proposed formulations.

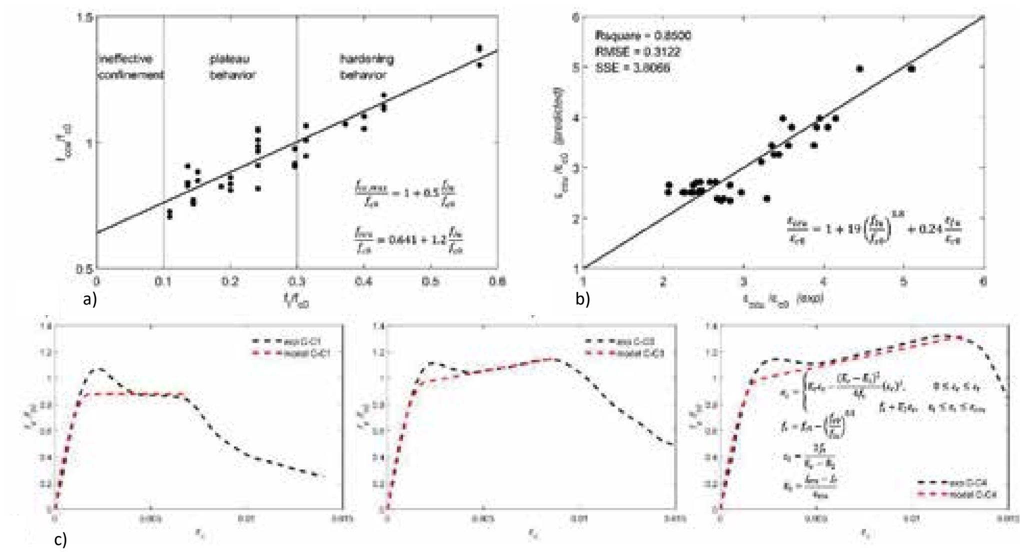


Figure 5. Ultimate stress and strain (a, b) and experimental vs. predicted stress-strain curves (c).

5. Concluding remarks and outlook

The results of four experimental campaigns are presented and a simplified design-oriented stress-strain model for FRCM-confined concrete is proposed. The experimental results prove that FRCM composites are a promising solution for retrofitting and repairing existing RC structures, as both their axial and seismic behaviours are improved.

Durability - especially at high temperature - of FRCM composites is one of the main issues where further research is needed. In addition, the use of bio-fibres should be investigated to reduce the carbon footprint of retrofitting interventions.

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Topic B

R/C AND P/C STRUCTURES
B1 - Testing and Modelling

B11 **MATTIA ANGHILERI** - Life-cycle structural performance of RC/PC bridges: computational modelling and experimental validation

B12 **ENRICO FACCIN** - An analytical and experimental study on the punching-shear strength of steel fibre-reinforced concrete flat slabs

B13 **STEFANO GIUSEPPE MANTELLI** - Long-term prestressing losses in bridge girders: on-site assessment and effect on the shear strength

B14 **CARMINE MOLITIERNO** - Pseudo-dynamic tests for seismic- performance assessment: facility development, verification and test reliability

B15 **SIMONE RAVASINI** - Structural robustness assessment of precast-concrete structures

B16 **ALESSIO RUBINO** - A fracture-mechanics approach for the design of fiber-reinforced and hybrid-reinforced concrete structures

LIFE-CYCLE STRUCTURAL PERFORMANCE OF RC/PC BRIDGES: COMPUTATIONAL MODELLING AND EXPERIMENTAL EVALUATION

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Keywords: bridges, life-cycle, reinforced and prestressed concrete, deterioration, corrosion, uncertainties, structural modeling, experimental validation

1. Introduction

Safe, reliable, robust, and sustainable bridges and infrastructure systems are the backbone of modern society, as they are the basis of economic growth and sustainable development. Bridge design has provided the opportunity for some of the most challenging applications of structural engineering. It is therefore a priority to protect, maintain, and manage aging bridges over their life-cycle. Aging and deterioration, combined with a low durability of materials and lack of proper maintenance and repair, can drastically affect bridge bearing capacity under the service loads, an urgent problem, particularly in Italy where concrete bridges built over the past 50 years are rapidly approaching the end of their service life. This critical situation is made more evident by recent bridge collapses. Moreover, today's traffic-induced loads are much higher than the design loads of the past. The continuously increasing traffic demand, the long-term exposure to aggressive environments, and the use of new construction materials and technologies, have favoured the development of a life-cycle approach that is now a driving force in structural engineering [1].

The thesis presents a life-cycle probabilistic framework for the assessment of the structural performance of reinforced- and pre-stressed concrete (RC/PC) bridges exposed to aging and deterioration, with the focus on corrosion. The diffusion process of chlorides inside concrete members is solved numerically through *Cellular Automata Algorithms*. Uncertainties are accounted for based on probabilistic methods and implemented by means of numerical simulation techniques, including *Subset Simulation Method*. The beneficial effects of new information gathered from diagnostics and maintenance activities are investigated using *Bayesian inference*.

Structural modelling is developed with different levels of complexity using either RC/PC beam FEs accounting for the material nonlinearities or bi-dimensional FEs for plane-stress analysis, in accordance with the Modified Compression Field Theory (MCFT). The proposed approach is validated by fitting (a) the results of several experimental tests available in literature on RC/PC beams, and (b) the measurements collected from an extensive experimental campaign (BRIDGE 50 Research Project, *bridge50.org*) on the residual performance of a decommissioned 50-year-old PC bridge.

2. Finite element models for the nonlinear analysis of RC/PC structures

Several finite element formulations for the nonlinear analysis of concrete structures are available in

the literature with distinctive features based on different factors, including element discretization and formulation, and the solution process. Here, a RC/PC beam-like finite element (BFE) is adopted as a trade-off among robustness of the formulation, accuracy of the solution process, and computational cost. The BFE assumes the linearity of the cross-sectional strain field, accounts for the material nonlinearities, and neglects shear failures and bond-slip of steel reinforcement. The structure is discretized into beam-like finite elements (Figure 1, left), the member cross-section is subdivided into four-node isoparametric subdomains, and numerical integration is adopted to handle material nonlinearities [2].
A plane-stress finite element model, formulated in accordance with the MCFT [3], is also adopted to better account for shear effects and local stress-diffusion phenomena. MCFT is based on a smeared rotating-crack approach and considers the cracked RC medium as an orthotropic material with its own constitutive laws. Equilibrium, compatibility and constitutive laws are formulated in terms of average stresses and strains, and the directions of both the principal stresses and the principal strains directions are assumed to be coincident. The structure is discretized into constant- strain triangles (CST), see Figure 1 (right) and the reinforcement is smeared [4].

3. Validation based on corroded RC beams

A selection of experimental tests available in the literature on corroded RC beams are considered to validate the finite element models. Test #1 [5] refers to RC beams with a span of 3.00 m and a rectangular cross-section (152×254 mm) subjected to accelerated corrosion in the midspan region. The simply-supported beams were tested in 4-point bending with a shear span of 1.00 m. The average steel mass loss of the beams was Δ_s = 8.9%, 14.2%, 22.2%, and 31.6%. Test #2 [6] considers RC beams with a span length of 2.00 m and a rectangular cross-section (150×200 mm). The simply-supported beams have been tested with two symmetrical loads at a distance of 20 cm from the midspan. Beam 111 was the reference beam (no corrosion). Beams 114, 115, and 116 were subjected to accelerated corrosion by adding calcium chloride to the mixing water.

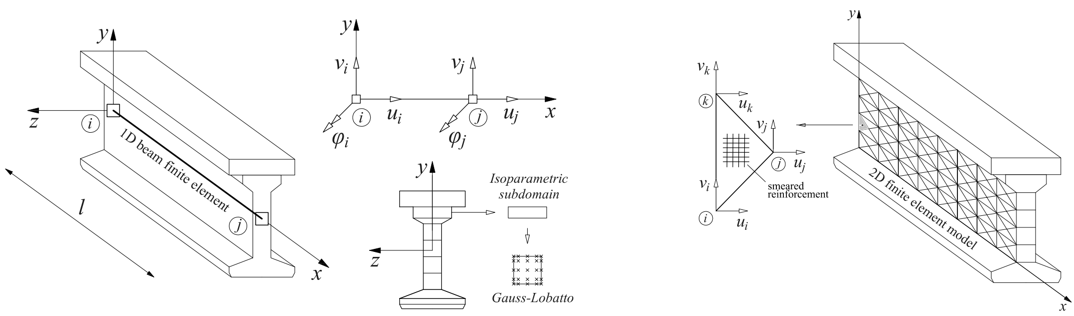

Figure 1. BFE model (left) with nodal displacements, isoparametric discretization and Gauss-Lobatto scheme; and MCFT model (right) with nodal displacements and discretization.

A BFE model is used for the numerical analysis of the experimental tests. Element discretization, isoparametric subdomains and integration sampling points are based on a trade-off between accuracy and computational cost. The uniform- and pitting- corrosion models described in [7] are adopted. The reduction of steel ductility and deterioration of concrete are also introduced. In Fig. 2 the experimental and numerical results are compared in terms of load versus midspan deflection (Test #1, Fig. 2, left, and Test #2, Fig. 2, right). A similar accuracy was provided by the MCFT model.

4. Validation based on a dismantled PC viaduct (BRIDGE 50 research project)

The BRIDGE 50 research project was a joint undertaking among the Academy (Politecnico di Milano and Politecnico di Torino), public authorities and private companies for an extensive experimental campaign on a dismantled 50year-old PC viaduct [8]. The experimental campaign included full-scale load tests on PC deck beams (Figure 3, left) with a length of 19.40 m, each provided with twenty 7-wire prestressing strands and supporting a cast-in-place RC slab. Concrete and steel mechanical properties were measured through non-destructive and laboratory tests. No sizeable corrosion of the prestressing strands was observed in the regions subjected to prevailing bending since corrosion mainly developed in the outer regions.

The deck beams were tested in 3- and 4-point bending, with and without the RC slab at the top. The results of several full-scale load tests were used to validate both the BFE and the MCFT finite element models. As an example, in Figure 3 (right) the experimental and numerical (MCFT) results concerning two beams tested in 3-point bending are compared in terms of load versus midspan displacement (the contributions of the self-weight and of the prestressing force are not included). In the application of the MCFT model to the PC beams provided with a top RC slab, separate finite- element meshes are introduced for the beam and the slab to account for a possible slip at the beam-slab interface. The nonlinear analysis is based a two-level incremental approach. Firstly, the self-weight and the prestressing force are applied to the beam. Secondly, the two separate meshes of finite elements (i.e., PC beam and RC slab) are connected at each pair of nodal points at the beam-slab interface by means of rigid links in the transverse direction and elastic links in the longitudinal direction. In the latter case, the stiffness of the connection is calibrated based on the test results.

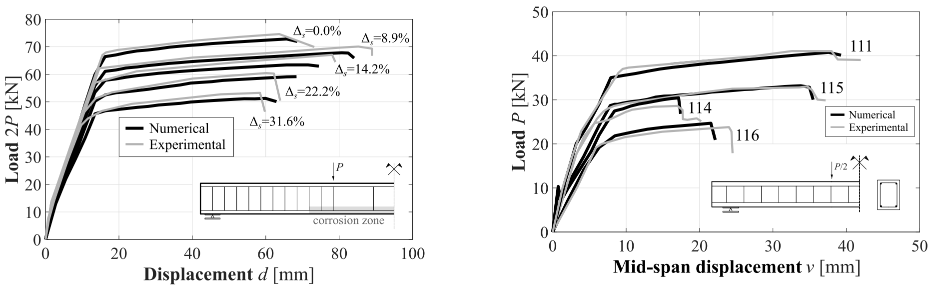

Figure 2. Comparison of experimental and numerical results in terms of load vs. midspan displacement: Test #1 (left); and Test #2 (right).

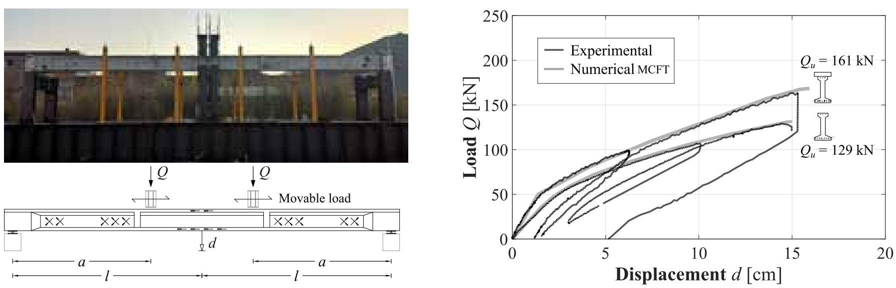

Figure 3. View of the test setup and of the 4-point bending test (left); and load vs. midspan displacement of the PC beams with/without top slab subjected to 3-point bending (right).

5. Concluding remarks

The validation of the finite element models for the nonlinear analysis of concrete structures based on BFE and MCFT formulations has been performed by comparison with some experimental tests available in literature and with the findings of a number of full-scale load tests on the PC beams extracted from a dismantled bridge. The agreement between numerical and experimental results is more than satisfactory. Further efforts will be devoted to the improvement of the proposed models for shear-dominant structural mechanisms. The contributions of this project are expected to advance the knowledge in the field of bridge management and to improve the existing methods for the assessment of structural and infrastructural safety, reliability and residual lifetime.

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Supervisor: *Professor Fabio Biondini*

EXPERIMENTAL AND ANALYTICAL STUDY ON PUNCHING SHEAR STRENGTH OF STEEL FIBRE REINFORCED CONCRETE FLAT SLABS

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Keywords: punching shear, steel fibre-reinforced concrete (SFRC), slab-column connections, experimental tests, Critical Shear-Crack Theory (CSCT), analytical model (for slab punching).

1. Introduction

Flat and thin or thick reinforced-concrete structures are commonly found in construction, as they combine simplicity with economic and functional advantages. In spite of their simple appearance, however, flat slabs exhibit a complex structural behaviour in bending and shear.
Punching is a shear-related failure mode, that generally occurs within the regions of discontinuity (D-regions), typically close to columns. Punching is a brittle-type failure unless accompanied by the yielding of the flexural reinforcement.
In the past 50 years, several collapses of RC flat slabs have occurred in the form of brittle punching, such as the "2000 Commonwealth Avenue" condominium collapse in Boston (1971), the "Sampoong" department store collapse in Seoul (1995), the "Pipers Row" car park collapse in Wolverhampton (1997), and the car park collapse in Santander (Spain, 2020).
Due to the relevance of this failure mode, punching shear has been intensely investigated, both experimentally and theoretically, the 1950's. In the past, several behavioral models have been developed. These models are either empirical (able to fit the experimental evidence) or mechanical (i.e., based on physical theories). Although mechanical models are more consistent and allow the designer to understand the physical phenomenon of punching shear, a number of current design codes [1,2] are still based on empirical models for the sake of simplicity.
In this research project, randomly-distributed hooked steel fibres are introduced into the concrete mix in order to increase the material's ductility and to improve the structural performance.
Furthermore, the experimental program developed in this project is so far a unicum. In particular, the use of five digital tilt-meters, the cutting of the specimens (after their failure), and the adoption of different geometries and fibre amounts have allowed the author to gather many data and to formulate a new model for the punching shear capacity of RC slabs. Note that the model takes care of fibre contribution and size effect as well.

2. Experimental program and results

In order to investigate the roles played by both size effect and fibre-amount on the punching-shear capacity of SFRC slabs, three series of slab-like specimens (Fig. 1) were tested: Series S250, S125, and S68 (where the digits indicate the total thickness in mm). The specimens of the three series were geometrically similar (as far as possible) and the steel ratio was roughly constant, to allow size effect to stand out (Table 1).

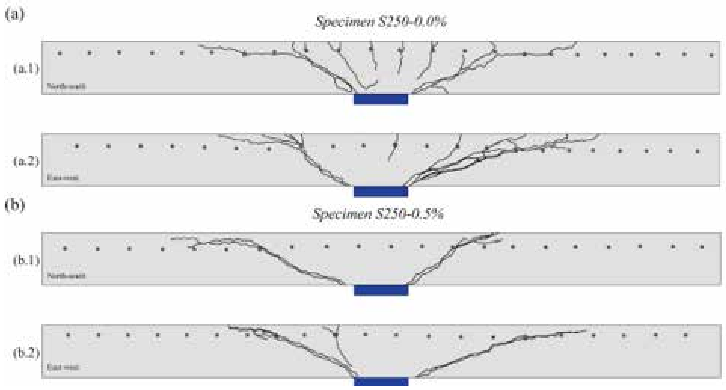

Figure 1. Typical slab-like specimens: (a) V_f = 0%, and (b) V_f = 0.5%; (a.1, b.1) north-south section, and (a.2, b.2) east-west section. The specimens are loaded from below.

Specimen	V_f	B [mm]	h [mm]	c [mm]	d [mm]	Top reinforcement	ρ
S250-0.0%	-	3240	250	260	210	ϕ 18 @ 150 mm (22 bars in each direction)	0.83%
S250-0.5%	0.5%	3240	250	260	210		0.83%
S250-1.0%	1.0%	3240	250	260	210		0.83%
S125-0.0%	-	1620	125	130	105	ϕ 10 @ 90 mm (18 bars in each direction)	0.83%
S125-0.5%	0.5%	1620	125	130	105		0.83%
S125-1.0%	1.0%	1620	125	130	105		0.83%
S68-0.0%	-	870	68	65	52	ϕ 6 @ 70 mm (13 bars in each direction)	0.78%
S68-0.5%	0.5%	870	68	65	52		0.78%
S68-1.0%	1.0%	870	68	65	52		0.78%

Table 1. Dimensions of the specimens and top reinforcement; V_f = steel-fibre amount by volume; B = side-length of the slab; H = total thickness of the slab; c = side-length of the column (square section); d = effective depth of the slab; ρ_s = flexural reinforcement ratio.

The reinforcement consisted of deformed bars with a yield strength varying between 518 and 558 MPa (steel B450C according to [3]).

Concrete compressive strength on cylinders was close to 37, 29 and 30 MPa for the specimens without fibre (plain concrete), with 0.5% fibre (FRC class 2c) and with 1.0%

fibre (FRC class 3b), respectively. The length, diameter, aspect ratio and tensile strength of the fibres are: 35 mm, 0.6 mm, 58 and 2000 MPa.

After the tests, the specimens were saw-cut to investigate the geometry of the critical shear cracks, as well as the number of the secondary flexural cracks contained within the punching cone. The main results of the tests are synthetized in Figure 2.

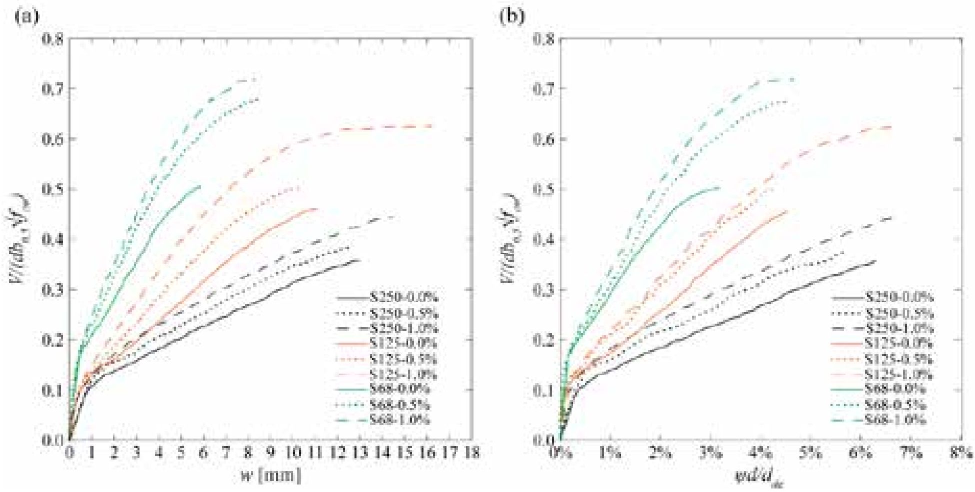

Figure 2.1 (a) Normalized shear capacity vs. mid-span deflection; and (b) normalized shear capacity vs. normalized mean rotation.

3. Analytical model

Based on the test results, a mechanical model has been proposed by extending a previously formulated model [4] to fibre-reinforced concrete.

	UNIBS	
Specimen	V_{exp}/V_u	ψ_{exp}/ψ_u
S-250-0%	1.01	0.87
S-250-0,5%	1.02	0.90
S-250-1%	0.92	0.74
S-125-0%	1.05	1.01
S-125-0,5%	0.98	0.80
S-125-1%	1.08	1.26
S-68-0%	1.09	0.92
S-68-0,5%	1.24	1.80
S-68-1%	0.96	1.23
Media	**1.04**	**1.06**
Dev.st	**0.09**	**0.33**
CoV	**0.09**	**0.31**
Only FRC	V_{exp}/V_u	ψ_{exp}/ψ_u
Mean	**1.03**	**1.12**
Dev.st	**0.11**	**0.40**
CoV	**0.11**	**0.35**

Table 2. Experimental vs. theoretical results in terms of capacity V and rotation ψ.

Fibre contribution was introduced into the mechanical model by modifying:

- the σ-ε relationship (in compression); - the residual tensile strength σ_{fct};
- the number of cracks (n_{cr}) in the critical area (punching cone; n_{cr} is assumed to be equal 1 in the preliminary applications of the model.

For FRC specimens, the mean value and CoV are indicated in the Table 2.

4. Concluding remarks

Based on the tests, the following main conclusions can be drawn:

- Steel fibres are effective as the experimental results show that fibre-reinforced slabs have an increment in terms of ultimate punching load (V_f=0.5% and 1.0%) and in terms of deformation capacity (more evident for V_f=1.0%). With respect to the plain-concrete slabs, the fibres increase the capacity and the deflection at the peak load from roughly 10% to 40%.
- Adding steel fibre does not change the structural behaviour before cracking.
- In fibre-reinforced slabs, cracking tends to become more stable at lower loads (compared to the ultimate load) than in the slabs without fibre.
- In fibre-reinforced slabs, the flexural cracks (i.e., the radial cracks included within the punching cone and opposed to the applied load, Editors' note) tend to become less numerous whenever the effective depth is increased.
- Smaller-thickness slabs have proportionally a larger punching-shear capacity than thicker slabs, which means that there is a fairly strong size effect, not mitigated – however - by steel fibre.
- The mechanical model looks promising, but its development is still in progress.

5. Outlook

The relationship between the number of the flexural cracks and the punching-related parameters (like effective depth, fibre amount and aspect ratio) is still a topic open to investigation. Similar considerations may be extended to the critical perimeter.
Last but not least, It is imperative to increase the database, by launching new experimental campaigns.

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Supervisor: *Professor Fausto Minelli*

LONG-TERM PRESTRESSING LOSSES IN BRIDGE GIRDERS: ON-SITE ASSESSMENT AND EFFECT ON THE SHEAR STRENGTH

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Keywords: prestressed-concrete structures, prestressing losses, shear behavior (of PC members), bridge girders, assessment (of prestressing losses)

1. Introduction

The assessment of the residual load-bearing capacity of precast prestressed reinforced-concrete bridge decks (PRCs) after more than 50 years of service is often a challenge, especially in case of degradation due to poor, deferred or missing maintenance or even to stress-induced cracking. Following an inspection program carried out on over 400 bridges in the Province of Brescia (North Italy), 6% of the PRC bridges (roughly 44% of the inspected assets) were found to be affected by shear-induced cracking in the webs, something unexpected under the usual loads.
The nature of these cracks may be attributed to various causes, including the overestimation of the contribution to shear resistance provided by the prestressing of the element during the design phase. From an in-situ survey and from the literature, it was found that in the 1970s-1980s the precast companies were used to produce prestressed elements with light or (in some cases) no shear reinforcement. This was also allowed by German regulations before the seventies in the design and production of prestressed elements [1-3].
The reason behind such a design approach was the conviction that prestressing markedly contributes to the shear resistance, with a significant saving in terms of transverse reinforcement.
This research project aims to investigate two aspects: the reliability of certain diagnostic techniques proposed in the literature for the assessment of in-situ prestressing, and the influence that prestressing losses may have on the crack pattern and on shear capacity of full-scale bridge beams.

2. Experimental program and analytical models

To meet the two previously-introduced objectives, an experimental program was carried out on 4 identical PRC beams (length = 10 m; section depth = 80 cm; web thickness = 18 cm) characterized by a I section and minimum web reinforcement. Two beams - provided with pre-tensioned strands - differed for the prestressing level (100% and 70% in Beam A and Beam B, respectively; in the latter case, the prestressing force was reduced to simulate a prestressing loss). The other two beams C1 and C2 (not treated here) had post-tensioned strands, that allowed the prestressing level to be controlled during the tests to represent different scenarios for long-term losses.
To set up a practical system for the on-site evaluation of the residual prestressing, three semi-destructive methods based on stress release were used: core drilling (Fig. 1-a), saw-cutting at the intrados (Fig. 1-b), and extraction of a blunt pyramidal specimen after locally saw-cutting the web along 4 inclined and adjoining planes (Fig. 1-c). In addition, a new application of saw-cutting was

carried out concerning the web (Figure 1-d), with 2 different depths of the parallel cuts (2 and 3 cm) and 2 different distances between the cuts (6 and 10 cm). This application of saw cutting to the web was also modelled via 2D and 3D finite elements assuming linear elasticity.

(a) (b) (c) (d)

Figure 1. Cutting methods for stress-release tests: (a) core drilling; (b) saw-cutting at the intrados; (c) extraction of a blunt pyramidal specimen; and (d) saw-cutting on the web.

Later, to investigate to what extent prestressing losses may influence the shear strength and the crack pattern, 3-point bending tests (Figure 2) were performed on the beams (shear span/section depth = 2.9), the evolution of the crack pattern was monitored via Digital Image Correlation (DIC) and the test results were compared with those provided by numerical analysis. The latter was performed by using the software VecTor 2 based on the Modified Compression Field Theory - MCFT) [4]

Figure 2 - Third-point bending test of a PC beam.

Finally, since the design equations for shear capacity proposed in the various codes (e.g. Eurocode EC 2, *fib* - Model Code, CSA) [5-7]) are very conservative in the case of prestressed elements with stirrups, an equation based on the draft LoA IIb of *fib* - Model Code 2020 is proposed in this project. This equation is shown to be very effective, as the theoretical results are in good agreement with some experimental results available in the literature, used for the validation of the equation.

3. Results

The proposed test method with two vertical parallel cuts on the web is the most reliable among the methods considered in this study. In particular, the geometry with the cuts 3 cm deep and 6 cm apart (a) provides the best results in terms of closeness to the analytical and numerical predictions, and (b) is on the safe side, as the actual prestressing force is underestimated by 10%, with a CoV of 21% (Figs. 3 and 4).

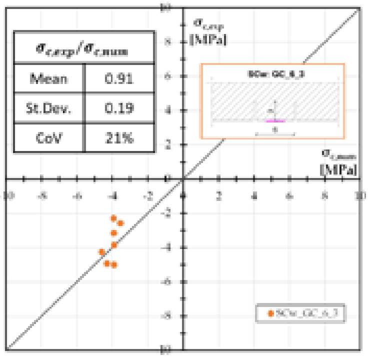

Figure 3. Dispersion of the experimental results () compared to the theoretical results () in GC-6-3 (*).

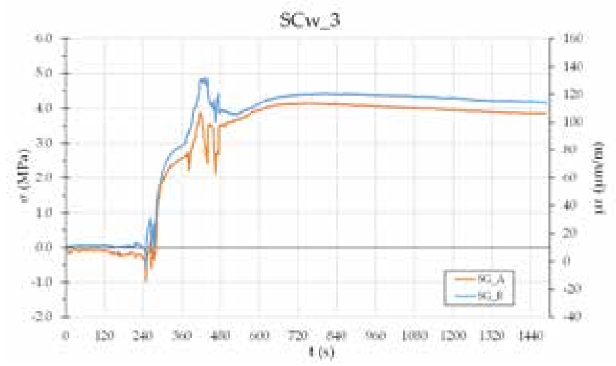

Figure 4. Typical output graphs (recorded from the gauges) during the stress release accompanying the creation of two cuts in the web. For SCw-3 see (**)

As for the shear tests under 3-point loading, one interesting result emerges from Fig. 5, where the shear-crack width is plotted as a function of the vertical load for Beam A (100% prestressing, top curve) and Beam B (approximately 70% prestressing, bottom curve).

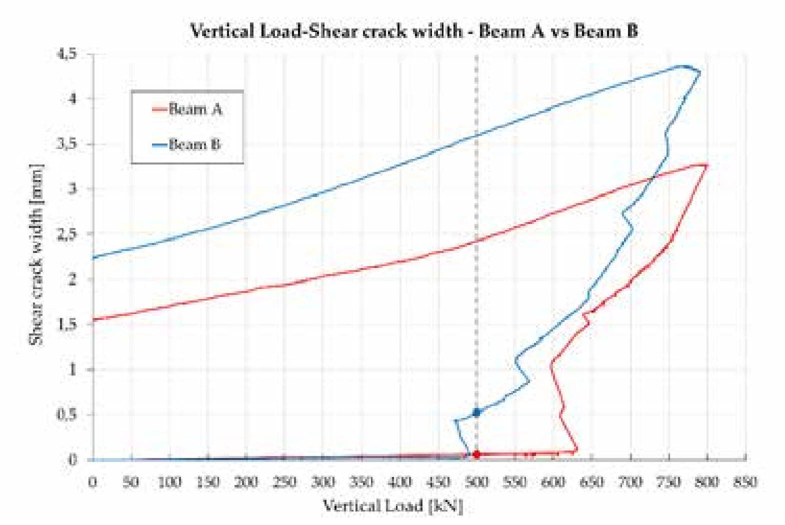

Figure 5. Evolution of the shear-crack width during the tests Of the two pre-tensioned beams (Beam A and Beam B).

The difference in the prestressing force between the pre-tensioned Beams A and B has a significant impact on the load causing the formation of the first diagonal crack and on the crack pattern at collapse: in the less prestressed Beam B, the first shear crack appears when the load is still close to the service load with full prestressing (Beam A); in the fully-prestressed Beam A, the shear cracks at collapse are thinner than in the less prestressed Beam B, where the shear cracks are wider and more distant.

(*) GC-6-3 = Geometric Configuration with cut distance = 6 cm; cut depth = 3 cm.

(**) SCw-3 = Saw-Cut-web, cut No. 3 (among the 15 cuts created in the webs).

4. Concluding remarks

The on-site evaluation of the residual prestressing force and its contribution to the shear capacity of existing PC beams are today topical issues, all the more because the shear behaviour of PC beams is brittle and hardly predictable through modelling.
This research project aims at contributing to the expansion of the database on the shear behaviour of PC beams and to the understanding of the effect that the prestressing force has on the shear capacity at different prestressing levels. An analytical model is proposed as well, to predict the shear capacity of PC beams. This model appears to be more realistic – but still on the safe side – compared to other models proposed by the structural codes

5. Outlook

The tests aimed at the on-site evaluation of the residual prestressing via concrete stress release are complex all the more because many variables must be taken into account (e.g. geometry of the cut, concrete porosity, strain-gauge size, temperature, expertise of the operators, …….). Hence, a further experimental campaign aimed at improving saw-cutting applied to webs - as well as the interpretation of the results - is underway.

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SEISMIC ASSESSMENT: EXPERIMENTAL FACILITY, VERIFICATION AND RELIABILITY

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Keywords: infilled RC frames, seismic assessment, nonlinear time history, substructuring, pseudo-dynamic tests, test reliability.

1. Introduction

The existing infilled reinforced concrete (RC) buildings of the Mediterranean area are vulnerable to seismic actions, as demonstrated by the damage to structural and non-structural components observed in the aftermath of recent seismic events [1, 2]. In this context, experimental investigation on seismic performance is crucial to improve the knowledge on the mechanical response and to develop/validate innovative strengthening solutions. The mechanical response is often characterized by the brittle response of the infills or by that of the structural system [3]. Experimental tests on full-scale prototypes are, therefore, required to accurately reproduce damage propagation and the hysteretic response. Only a few tests on full-scale infilled RC multi-storey structures, however, are available in the literature, because of the limitations in the test facilities. Recently, a pseudo-dynamic (PsD) test setup has come into operation at the Laboratory for testing real-scale STRUcTures (LaSTRUT) within the center CeSMA of the University of Naples "Federico II". The objective is to enable scholars and researchers to carry out tests on full-scale building prototypes or subassemblies. This thesis is focused on the development of both the test facility and the control system, in order to allow the entire system to run PsD tests. A four-storey infilled RC building damaged by the 2009 L'Aquila earthquake was identified as case study. The most damaged outside frame was selected and reproduced in the laboratory to be tested with various infill-to-frame connections and to quantify their effect on the global and local response of the frame.

2. Test facility and experimental program

The facility for large-scale PsD tests available at the LaSTRUT of the University "Federico II" is shown in Figure 1. It is an indoor facility equipped with an L-shaped reaction wall and with a strong floor [4]. The test facility consists of two hydraulic actuators fastened to the reaction wall, which operate in the displacement-controlled mode. The gravity loads are applied via two hydraulic actuators located at the top of the columns. The displacement imposed to the specimen is measured by two transducers fastened to a reference frame. The specimen is restrained to the strong floor by means of prestressed bars and additional shear-transfer steel systems.
The above-mentioned case-study building (built between 1972 and 1981) belonged to the database of RC buildings heavily damaged during the L'Aquila earthquake [5]. Due to the height limitations of the reaction wall and to avoid the scaling of the specimens, only the most damaged outside frame ending with a corner column was selected and reproduced in full-scale. The prototype consists of a 1-bay/2-storey infilled RC frame (width = 4.10 m and height = 6.30 m high). The interstorey height is 3.10 m for

each floor. The reinforcement details are in accordance with the construction practice of roughly fifty years ago (i.e. no seismic details).

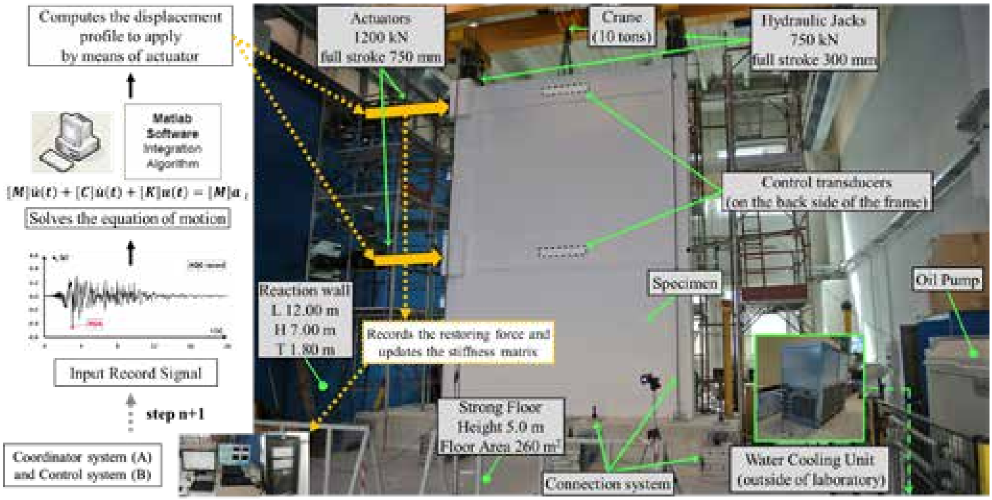

Figure 1. Test setup and PsD testing facility for the full-scale tests on infilled RC frames.

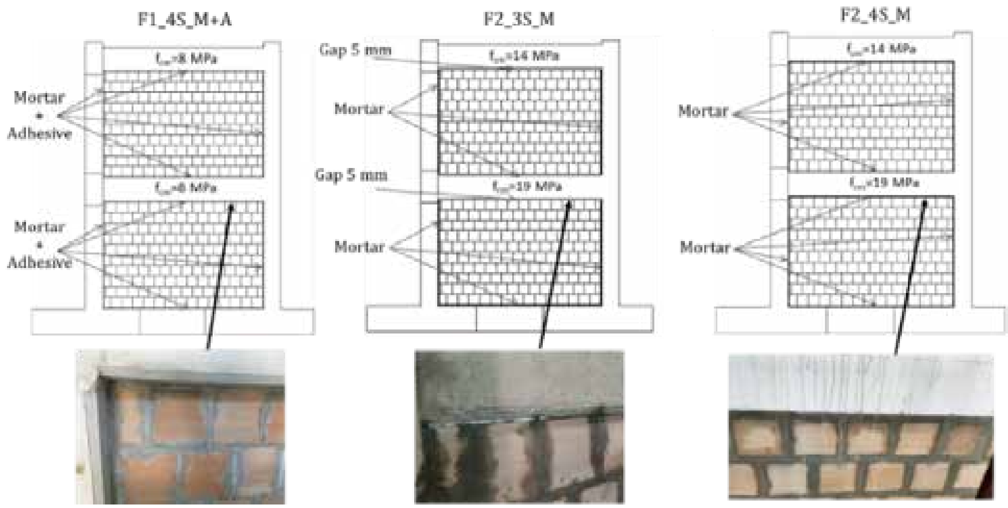

Figure 2. Details of the infill-to-structure connection in the three tests.

To investigate the infill-to-frame connection at both floors, three different frames, labelled F1 and F2, were built [6] (Figure 2). In the first frame F1-4S-M+A, the connection along the four sides (4S) is a full connection based on a traditional mortar (M) with the addition of a flexible adhesive (A) placed between the mortar and the concrete surface. In the second frame, two different connections are used, with traditional mortar (M) applied along three (3S) or four sides (4S). In the F2-3S-M frame, a 5 mm gap between the bottom side of the beam and the top surface of the infill surface was created during the erection of the wall, while in the F2-4S-M frame the connection is identical to that used in

the F1-4S-M+A frame, but without the adhesive.
The full-scale infilled RC frames with different infill-to-frame connections were tested using the PsD testing facility. The accelerogram used in the tests is the same as in the 2009 L'Aquila earthquake. It was scaled to different intensities (i.e., 10%, 25%, 50%, 75%, 100%, 125% and 150%) to allow the frame response to get stabilized and to create a progressive damage. At this stage, only in-plane actions were considered and the influence of out-of-plane loads was neglected. At the top of the columns, vertical loads (= 300 kN) were applied and kept constant throughout the tests.

3. Results

The backbone curves of the global response of the three frames are reported in Figure 3. The comparison shows that the initial elastic stiffnesses of the three frames are very similar. The more effective the connection between the infill and the frame, the greater the strength and stiffness of the infilled frames. In fact, specimen F2-3S-M has the lowest strength and stiffness due to the partial connection with a gap between the beam and top side of the infill. Specimen F1-4S-M+A with a full connection and a perfect bond between the infill and the frame has the highest strength while Specimen F2-4S-M has an intermediate behaviour. Moreover, the lateral response of F1-4S-M+A is very similar to that of Specimen F2-4S-M at the peak load, because the contribution of the adhesive vanishes.

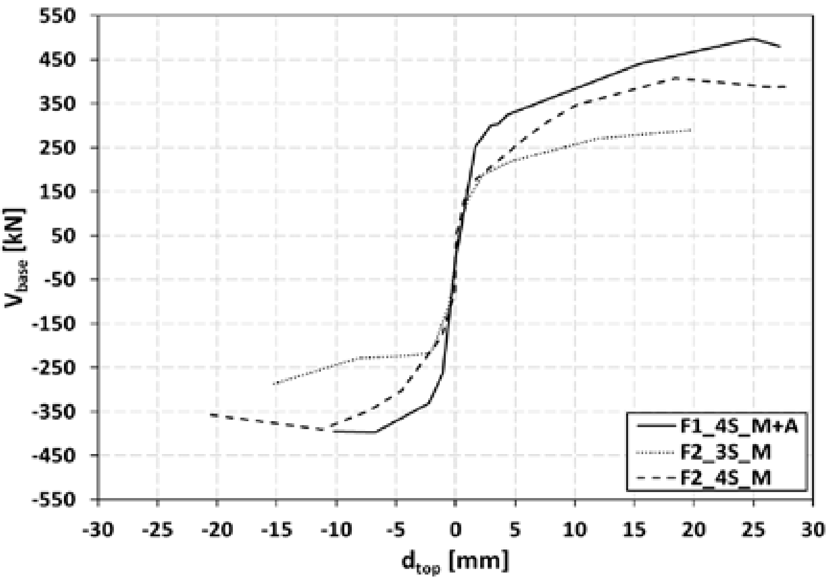

Figure 3. Global-response backbone curves of the frames tested in this research project.

Figure 4 shows the crack patterns and the damage in the case-study building (Fig. 4 left) and in one of the frames tested in the lab (Fig. 4 right). It is possible to observe that the crack pattern observed after the test - with multiple inclined shear cracks - well matches the crack pattern observed in the real building, as a demonstration of the validity of the proposed experimental procedure in capturing column failures in shear as a result of infill-to-frame interaction.

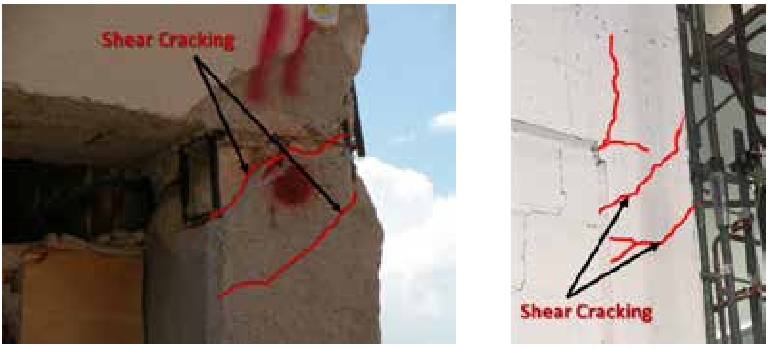

Figure 4. Observed damage in the real building (left) and in one of the frames tested in this research project (right).

4. Concluding remarks and outlook

The proposed pseudo-dynamic test procedure and the test facility for the full-scale testing of RC frames can accurately reproduce the earthquake-induced damage in existing buildings provided with multiple RC frames. The experimental results clearly show the influence that infill-to-frame connections have on the structural response, as well as the damage to both infills and RC frames.
The improvement of the performance of the pseudo-dynamic test facility in order to increase its reliability, and the introduction of out-of-plane actions are two of the issues still open to investigation.

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STRUCTURAL ROBUSTNESS ASSESSMENT OF PRECAST CONCRETE STRUCTURES

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Keywords: structural robustness, precast concrete structures, nonlinear static/dynamic FE analyses, simplified analytical approaches, design procedures

1. Introduction

During their service life, buildings may be subjected to extreme events such as earthquakes, tsunamis, explosions, fires and terroristic attacks. Such events may cause a local damage in the structure which could lead to the partial or complete collapse with considerable human, material and costs losses. Current codes and guidelines adopt mitigation strategies for unidentified accidental actions and use the following methods to assess structural robustness: (i) the Tie Force, (ii) the Alternate Load Path and (iii) the Key Element. In particular, the Alternate Load Path method takes care of the ability of a structure and/or sub-assembly to redistribute the applied loads and to develop alternate load paths to resist the local damage caused by the loss of a load-bearing member [1,2,3]. Several works for reinforced concrete (RC) monolithic structures and steel assemblies are available, with little attention to masonry, timber and precast concrete (PC) systems [4,5,6].
In the Thesis, a numerical approach and an analytical framework are proposed for the structural robustness assessment of PC structures under accidental actions. A procedure for the design of adequate tying reinforcement is proposed as well.

2. Sections of the work

The work is divided into three main sections. The first section deals with (a) a literature survey on the progressive collapse of precast concrete structures, (b) the proposal and validation of a numerical approach to reproduce the static and dynamic behaviours of monolithic and precast concrete structures subjected to the loss of a load-bearing member (such as a column), and (c) the evaluation of the resisting mechanisms (i.e. flexural/arch and catenary stages) with reference also to the joints and to PC members. The second section concerns the application of the numerical approach to a selected case study consisting of a precast concrete building with dry beam-to-column connections (with steel dowels) and hollow-core (HC) slabs. Concentrated ties (in beam-to-column joints) and distributed ties (in hollow-core units) are assumed to resist a progressive collapse through their tensile-catenary action. Tying reinforcement may consist in rebars or strands across joints and along resisting members. Different column removal scenarios (interior, peripheral and corner) are also considered. The third crucial section aims at proposing a simplified analytical framework to check or to design an adequate tying reinforcement in PC structures to support and redistribute the gravity loads after the loss of a load-bearing member. Design suggestions and detailing solutions are also discussed.

3. Numerical and analytical approaches

The first section aims at developing a simplified numerical approach (Seismostruct) with fibre-based elements for beams, columns, and slabs. The beam-to-column connections are modelled with link elements characterised by moment vs. rotation and shear load vs. displacement relations to reproduce the flexural resistance and the shear capacity of the metallic dowel devices at joints (Fig.1a). A similar approach is adopted for double-span hollow-core (HC) slabs, where the tying reinforcement can be placed (rebars, modelled at joints as link elements with axial load vs. slip relationship, or strands, modelled as continuous truss elements) across joints and along members (Fig. 1). The proposed numerical approach can correctly reproduce the load vs. displacement and dynamic response with limited computational costs.

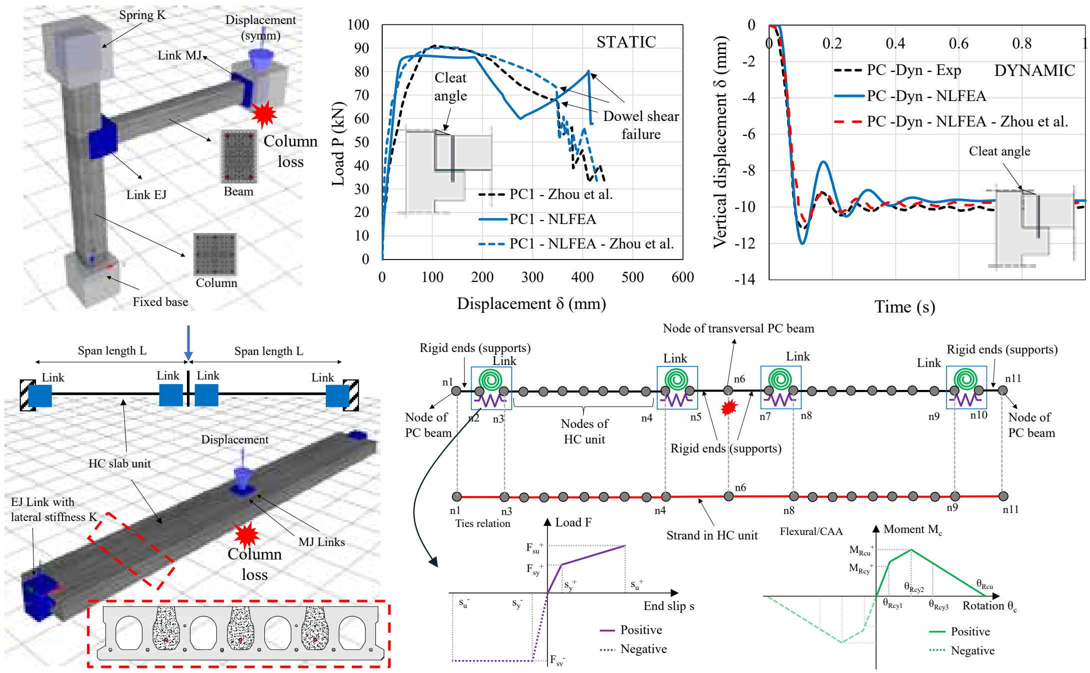

Figure 1. Modelling and results of PC frames and HC floors [5,6,7].

In the second section, the numerical approach (with both static and dynamic analyses) is extended to a selected PC building [5,6]. It can be observed that the flexural and catenary action mechanisms in HC floors and beam-to-column joints can be activated in case of interior column removal. In case of peripheral column removal, the catenary action of ties in HC floor is inhibited due to the lack of continuity. In the case of a corner column removal, the flexural resistance is the only mechanism that can be mobilised to resist progressive collapse. Such results show that ties in HC floor units govern the overall resistance in both the flexural and the catenary stage.

Finally, in the third section, an analytical framework is proposed. As shown in Figure 2, the load-displacement response of double-span HC units with distributed ties consists of three phases: yield phase (A, flexural/arch resistance), transition phase (B, from flexural to catenary) and catenary phase (C, where ties act like cables and the resistance of the system relies on the axial capacity and ductility of ties). Such concepts are valid also for concentrated ties in beam-to-column joints.

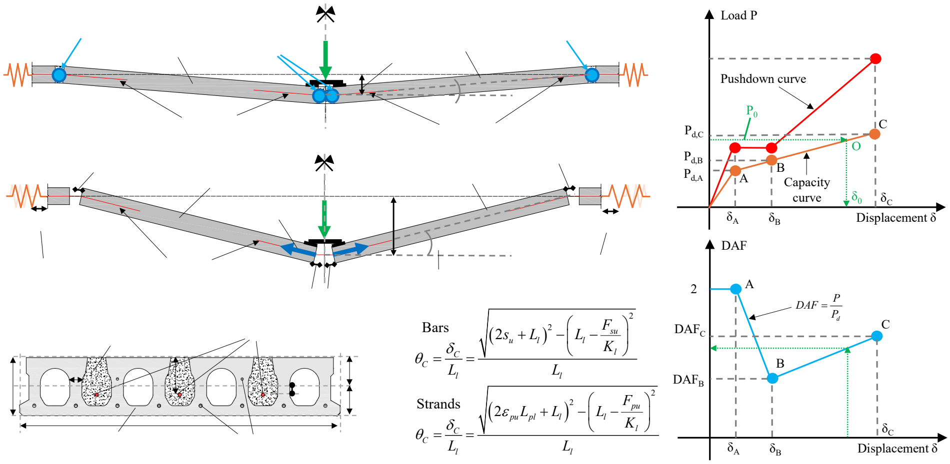

Figure 2. Analytical proposal for double-span HC units with deformed shape and equilibrium conditions: flexural/arch and catenary stages [8].

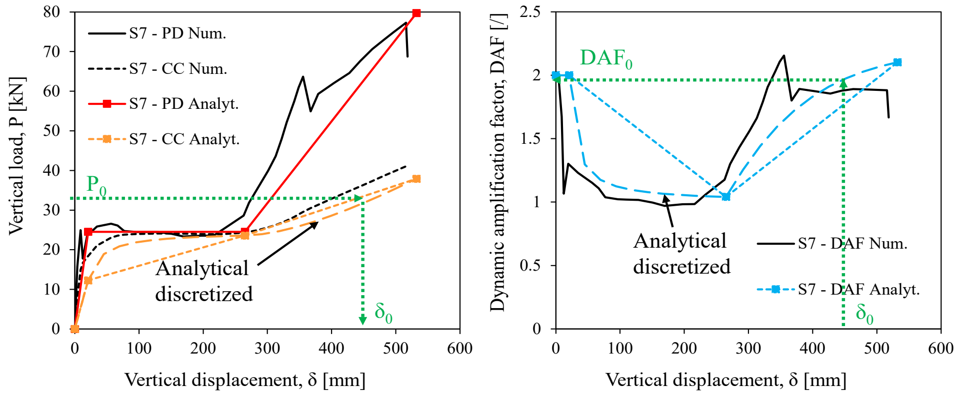

Figure 3. Analytical approach: static and dynamic responses [8].

The static and dynamic responses and the dynamic amplification factors are calculated as shown in Fig. 3, where the maximum dynamic displacement (δ_0) of the HC floors subjected to column removal and gravity load P_0 is shown as well. Comparisons against experimental tests are also available in [8]. The novelty of the work consists in the introduction of the parameters concerning the resistance to progressive collapse: (i) the compressive strength of the cementitious grout at joints, (ii) the strength and ductility of the tying reinforcement (rebars or strands), (iii) the geometry (such as cross-section size and the span length), and the restraining stiffness. The proposed calculation of the chord rotation capacity, θ_c, allows to assess the progressive-collapse performance and ductility of the system, related to the ability to develop a catenary action, depending on the rebars or strands used as ties (Fig. 2). The method is extended to an entire precast concrete floor by considering the role of concentrated ties in the beams. The comparisons with numerical results confirm the suitability of the proposed analytical approach. A design procedure is also introduced to design an adequate tying reinforcement in PC structures to guarantee a progressive collapse. (In fact, robustness is not sufficiently taken into account by current Eurocode provisions [8,9]).

4. Concluding remarks and outlook

The main findings of this work are related to: (1) the assessment of the resistance to progressive collapse in PC structures, with the focus on hollow-core floors, and (2) the design of adequate tying reinforcement in hollow-core floors and beams based on a rational mechanical approach. The proposed framework is aimed at practical purposes.

Experimental campaigns and detailed numerical approaches are needed to further evaluate the progressive-collapse resistance of real-scale hollow-core floors and to improve the current proposals and provisions.

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Supervisor: *Professor Beatrice Belletti*

A FRACTURE MECHANICS APPROACH FOR THE DESIGN OF FIBRE-REINFORCED AND HYBRID-REINFORCED CONCRETE STRUCTURES

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Keywords: fracture mechanics, fibre-reinforced concrete - FRC, FRC modelling, bridge effect (in fibre-reinforced sections), hybrid fibres, size effect, minimum reinforcement

1. Introduction

Significant efforts have been made in the last fifty years to understand the influence of fibres on the mechanical behaviour of concrete, even in combination with ordinary reinforcement. Despite the large amount of research work, however, very few investigations have been aimed at defining the minimum reinforcement condition, i.e., the minimum amount of steel rebars and/or short fibres (generally steel fibres) necessary to make the flexural capacity of a structural member larger than the capacity at first cracking.
To fill the above-mentioned gap, a fracture mechanics-based model is proposed in this research project, i.e., the Updated Bridged Crack Model (UBCM), for the minimum- reinforcement design of fibre-reinforced concrete (FRC) and hybrid-reinforced concrete (HRC) beams. Starting from an existing version of the model (Bridged Crack Model [1]), the "updating" consists in the implementation of appropriate constitutive laws in order to make the model able to describe the response of FRC and HRC members subjected to bending, whatever the type of fibre.
In the following sections, the main features of the model are presented, together with some applications regarding the minimum reinforcement in several cases well documented in the literature. Reference will be made to steel fibre.

2. The Updated Bridged Crack Model

The Updated Bridged Crack Model (UBCM) focuses on the crack propagation process occurring at the critical cross-sections of reinforced brittle-matrix composites (Fig. 1) [2]. Cross-section analysis is based on the following analytical conditions: (i) *crack propagation condition*, which is defined within the framework of Linear Elastic Fracture Mechanics (LEFM), whereby a crack propagates when the global stress-intensity factor, K_I, reaches the matrix fracture toughness, K_{IC}; (ii) *reinforcement constitutive laws*, which provide a direct connection between the bridging force, F, and the corresponding crack opening displacement, w; and (iii) *displacements compatibility conditions*, whereby the crack opening is calculated as a function of the applied bending moment, M, and of the distribution of the closing forces.

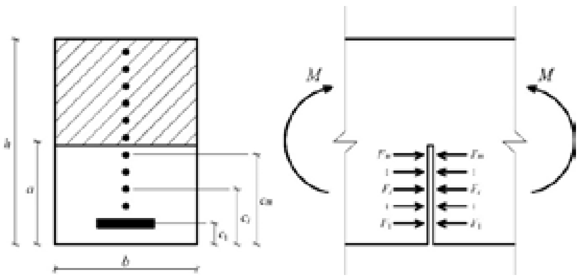

Figure 1. UBCM modelling of a cracked reinforced cross-section.

According to this approach, the model is able to describe the evolution of the fracture process and to describe the flexural behaviour in terms of load vs deflection curves [3]. The response is found to be synthetically described as a function of the three scale-dependent dimensionless numbers [4]:

(i) *bar-reinforcement brittleness number*, $N_P = \rho \frac{\sigma_y}{K_{IC}} h^{-1/2}$; (ii) *fibre-reinforcement brittleness* number, $N_{P,f} = V_f \frac{\sigma_s}{K_{IC}} h^{-1/2}$; (iii) *pull-out brittleness number*, $N_w = \frac{E w_c}{K_{IC} h^{1/2}}$. N_P is proportional to the steel-bar area percentage, ρ, and controls the level of the plastic plateau of the response. $N_{P,f}$ is proportional to the fibre volume fraction, V_f, and controls the contribution of fibres to the load-bearing capacity of the composite. N_w controls the evolution of the bridging action of the fibres, up to the exhaustion of this effect.

The minimum-reinforcement condition in FRC and HRC flexural members is described by a design nomograph in which the critical values of N_P and $N_{P,f}$ are linearly connected (Fig. 2). All the other parameters being the same, the linear relationship of Fig. 2 can be translated into a linear relationship between the minimum steel-bar area percentage, ρ_{min}, and the corresponding minimum fibre volume fraction, $V_{f,min}$. Within this context, the design nomograph can be used as a design tool to quantify the amount of fibres that is necessary for a partial, or even total, replacement of ordinary rebars.

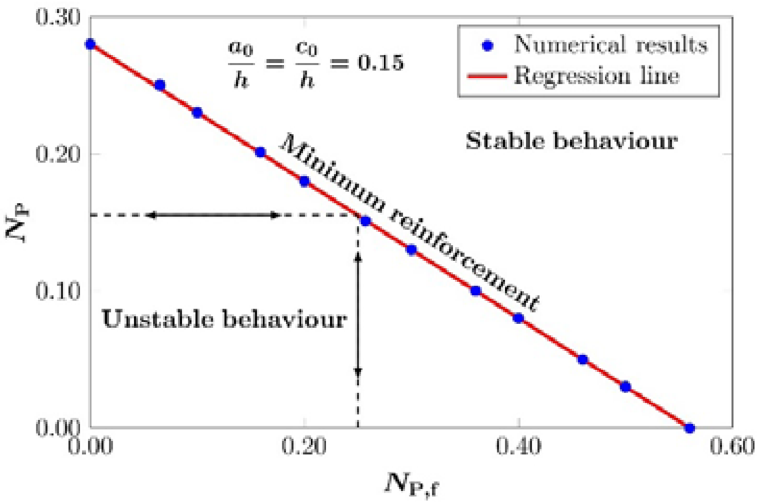

Figure 2. Minimum-reinforcement design nomograph.

3. Experimental assessment

With reference to several well-documented cases examined in a number of experimental campaigns (on both FRC [5-9] and HRC [10-12] beams), the proposed model has been used to check whether the minimum-reinforcement condition has been met. Within each experimental campaign, the mechanical properties of the concrete and of the reinforcement have been extracted in order to enable the model to predict the flexural response as a function of the amount of the reinforcing phases, i.e., ρ and V_f. Then, the design nomograph of Fig. 2 has been used to evaluate ρ_{min} and $V_{f,min}$ for each experimental campaign. In Fig. 3 the experimental curves are plotted together with the numerical curves provided by UBCM and referring to the minimum reinforcement. The numerical predictions allow to check whether the beam-like specimens tested in each experimental campaign are over- or under-reinforced.

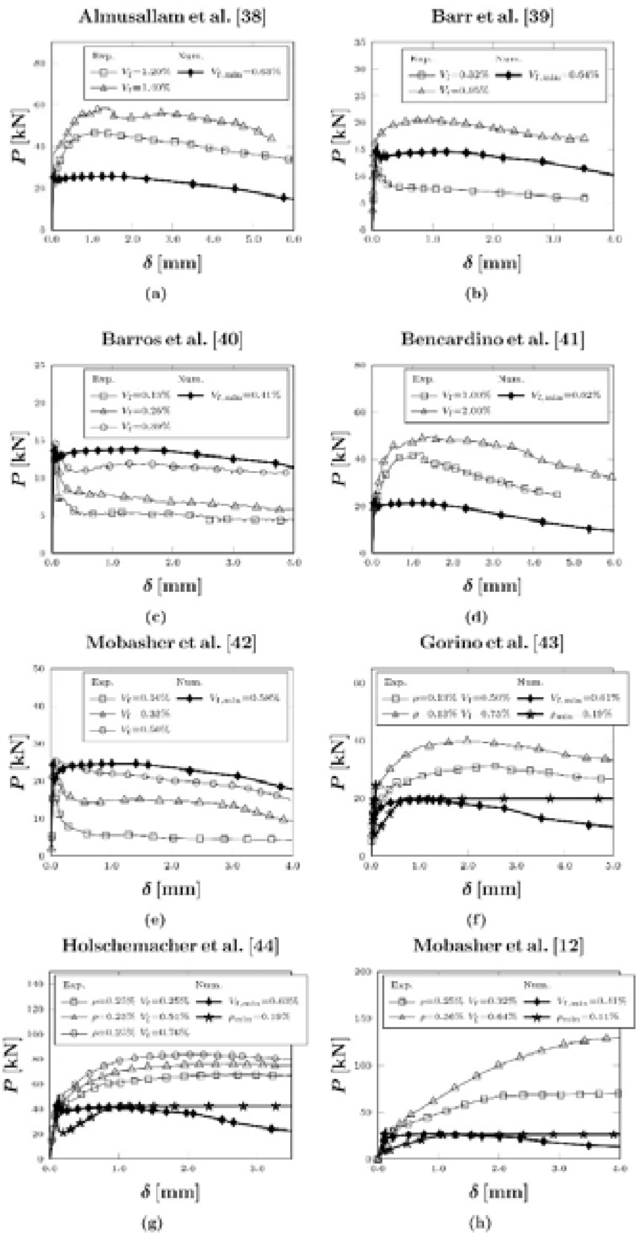

Figure 3. Experimental results vs minimum reinforcement prediction.

4. Concluding remarks

The Updated Bridged Crack Model (UBCM) is proposed as a fracture mechanics-based tool to design fibre-reinforced and hybrid-reinforced concrete beams (FRC- and HRC-beams) in accordance with the minimum-reinforcement condition. The effectiveness of the model has been proved by the comparisons with the response curves of several differently-reinforced beams tested in a few well-documented experimental campaigns based on steel fibre.

5. Outlook

The extension of the proposed model to mixed-mode crack propagation (Mode II) is an issue open to further investigation. Based on this approach, the effect of the reinforcing fibres on the shear behaviour of ordinary reinforced concrete beams can be investigated, making it possible to quantify the amount of fibres necessary to replace the shear reinforcement (stirrups).

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Topic C

DURABILITY AND EXTREME CONDITIONS

C01 **SALAM MAYTHAN JABER AL-OBAIDI** – Durability-based design of UHPC structures - From material to structural scale

C02 **MARTA CASTELLINI** – Experimental investigation on the durability of heritage concrete structures under environmental actions

C03 **RAMIN YARMOHAMMADIAN** – Fracture instability of heated concrete: a reassessment of the fundamental mechanisms behind explosive spalling

DURABILITY-BASED DESIGN OF ULTRA HIGH-PERFORMANCE CONCRETE (UHPC) STRUCTURES: FROM MATERIAL TO STRUCTURAL SCALE

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Keywords: ultra-high-performance concrete (UHPC), autogenous self-healing, durability of cracked UHPC, durability-based design, UHPC full-scale applications, cracked UHPC under sustained loads.

1. Introduction

Concrete consumption around the world has grown with the development of infrastructures and the extension of inhabited areas. Moreover, most of the existing structures subjected to severe environmental conditions suffer from durability and time-dependent problems. As an example, the cost of corrective and preventive maintenance can reach 30% of the annual operating budget in chemical plants. Since its introduction in the mid-nineties, Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) has proven to be an excellent material in providing structural strength and durability. The uniqueness of UHPFRC relies on its multi-cracking regime, with the micro steel-fibres controlling crack width and providing a significant ductility.

The self-healing capability of the material can effectively heal the thin cracks within a reasonably-short time thanks to the interaction with moisture. The current study - developed within the framework of the ReSHEALience project [1] – has two main objectives: (a) the development of a durability-based design methodology concerning the service life of UHPFRC structures, and (b) the spreading of the use of Ultra High-Performance Fibre-Reinforced Concrete. The Durability Assessment-based Design (DAD) methodology - set up on laboratory results and in-situ monitoring - is used, and structural applications of UHPFRC are presented to emphasize the work necessary to exploit in the best possible way the outstanding structural properties of UHPFRC at the serviceability, ultimate and durability limit states.

2. Experimental program and analytical models

Tests at different scales have been carried out to identify a durability-based design procedure, within a performance approach, as shown below:

<u>1 – Micro-scale level</u>: the bond-slip behaviour between micro steel-fibres and ultra-high-performance concrete has to be first investigated to understand to what extent bond is affected by matrix's self-healing in different exposure conditions. Some samples were partially pre-damaged under a controlled preload (fibre pre-slip at different load levels); then, the samples were subjected to one-month exposure in a 3.5% NaCl aqueous solution and to tap water, to study fibre corrosion and self-healing; later, pull-out tests were performed to compare the results of the tests on pre-damaged samples with those of the tests on initially undamaged samples (same curing history in all cases).

2-Meso/Macro-scale level: a long-term comprehensive experimental campaign has been carried out on small-scale beam specimens (500 mm long and 100 mm wide, with a nominal thickness of 30 mm). The specimens were subjected to long-term (up to one year) simultaneous exposure to sustained loadings and aggressive environmental conditions, represented by chloride or sulphate-rich solutions. Flexural capacity and stiffness were evaluated after each month of exposure.
3-Structural-scale level: three full-scale “pilot structures” (open tanks containing geothermal water coming from the cooling tower of a geothermal plant) were designed and built using either ordinary reinforced concrete or a durability-enhanced UHPFRC. After the construction and during the service life, the tanks were monitored and periodically checked to validate the assumptions adopted in the structural design, with specific reference to the long-term properties of UHPFRC [2].
Among the objectives of the design and construction of the pilot structures the following three should be mentioned: (a) tailoring the mechanical performance of the proposed UHPFRCs with reference to the long-term structural behaviour; (2) assessing the deterioration to improve service-life predictions; and (3) checking the in-situ behaviour of thin-walled structures devoid of ordinary reinforcement. The phases of the experimental campaign and of analytical modelling are described in Fig. 1.

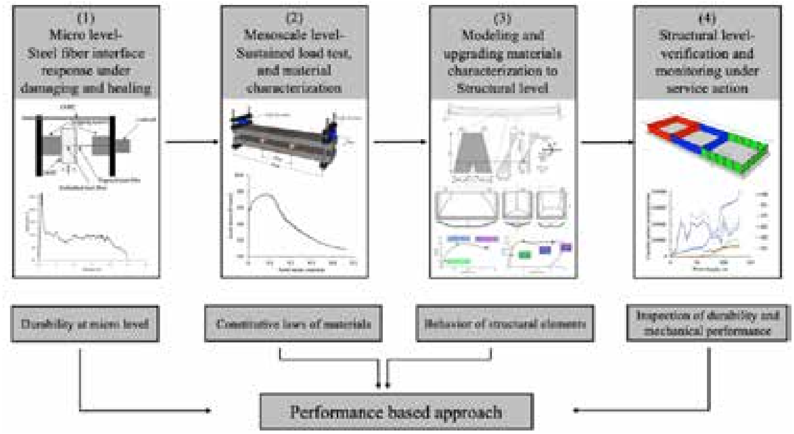


Figure 1. Phases of the proposed Durability Assessment-based Design - DAD methodology.

3. Results

Among the many, the single fibre pull-out test shown in Figure 2 reveals the significant healing (with the recovery of the damage) in the fibre-to-matrix contact layer.

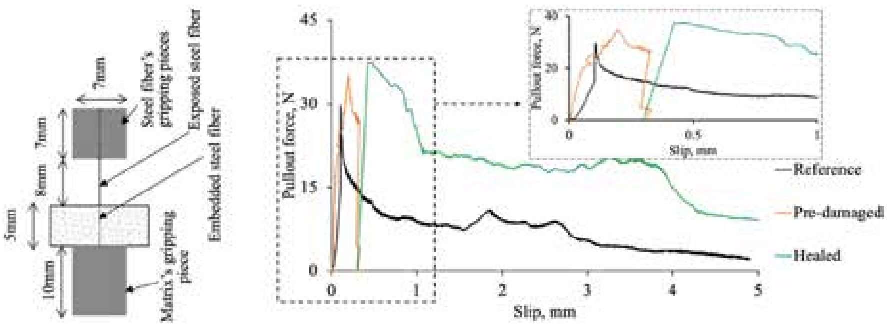
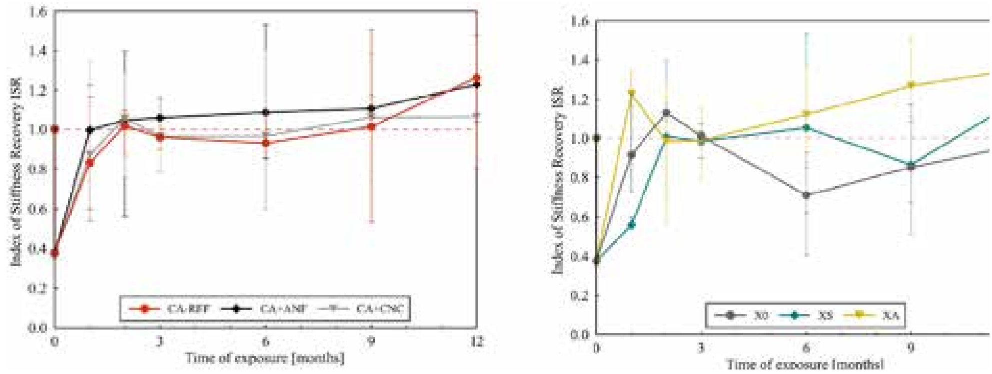


Figure 2. Pull-out test on a single micro steel-fibre and its performance after the healing of the microcracks in the concrete embedment.

The stiffness recovery in the UHPC beams (CA-REF/CA+ANF without/with added alumina nanofibers; CA-CNC with cellulose nanocrystals) is shown in Fig. 3 [3] after a 40% induced damage. The healing process occurred under sustained loads and during the exposure to freshwater – XO, chloride solution - XS, and geothermal water – XA.

F



igure 3. Results at the meso level: mechanical recovery after healing.

The constitutive tensile laws were derived by inverse analysis from the load-deflection curves of the specimens tested under simultaneous loading and exposure conditions. These laws were implemented into a nonlinear-analysis code to convert deflections into rotations, and loads into moments. Then, the use of the Yield-Line Theory made it possible to identify the failure mechanisms in order to evaluate the flexural capacity of the UHPC plates of the open tanks (Fig. 4). After 100 years, the capacity of the tanks decreases due to the chemical attack, by 30% in the third tank (UHPFRC, collapse of the 30 mm-thick precast walls) and by 21% in the second tank (UHPC, collapse of the 60 mm-thick cast-in-place bar-reinforced walls). Nonetheless, in both cases the predicted performance is still above the minimum required level.

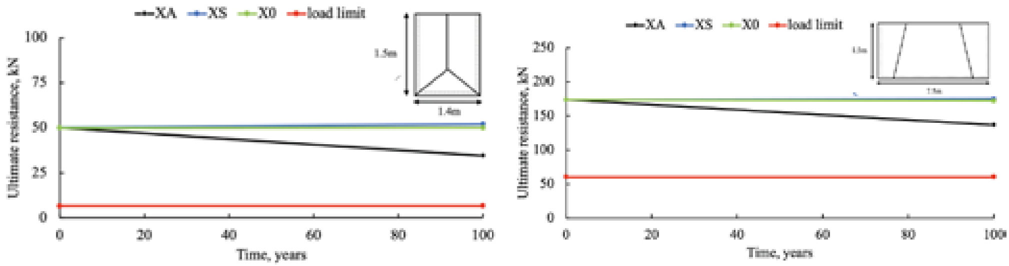


Figure 4. Open tanks after the acid-attack: performance of the walls of the third tank (left, 30 mm-thick precast UHPFRC walls) and of the second tank (right, 60 mm-thick cast-in-place UHPC walls reinforced with ordinary bars).

4. Concluding remarks

Durability Assessment-based Design methodology - DAD is proposed in this research project by implementing the constitutive behavioural laws of UHPFRC into an analytical model to predict the long-term performance of UHPFRC panels and structural components in service conditions. This approach may be used to move from the durability performance at the materials level to that at the structural level.

The results of the DAD approach confirm the superior performance of UHPFRC members, whose long-term mechanical performance is made significantly more stable by introducing nano additions into the cementitious mixes and by favoring the autogenous or stimulated self-healing of the cracks.

5. Outlook

To codify the strength recovery made possible by self-healing and stimulated healing, and to achieve the sustainability goal associated with the use of UHPFRC, cheaper constituents should be developed and introduced to guarantee the structural long-term performance.

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Supervisor: *Professor Liberato Ferrara*

EXPERIMENTAL INVESTIGATION ON THE DURABILITY OF HERITAGE CONCRETE STRUCTURES UNDER ENVIRONMENTAL ACTIONS

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Keywords: concrete durability, deterioration mechanisms, accelerated ageing, durability-related properties, concrete impregnation treatments, heritage (concrete structures)

1. Introduction

Durability of existing concrete structures under environmental agents is an aspect of outmost importance, as it is strictly related with the topic of the sustainability of concrete heritage [1]. Moreover, when dealing with structures of cultural interest, the evaluation of the limit states associated with durability is fundamental for the development of effective strategies aimed at preventive conservation [2]. Considering durability indicators and damage-sensitive properties, the reliability of the parameters to be introduced into the models is mainly related to the availability of literature data from realistic accelerated tests together with measurements on existing structures [3]. Limited research efforts, however, have been dedicated to the latter aspect.
The main objective of this research project is to compare the natural ageing process of a case-study (almost 50 years old) with the accelerated ageing of concrete samples with the same mix design, under four different environmental actions. In particular, the effect of each environmental action on concrete durability-related properties is analysed by considering the main mechanical and chemo-physical parameters. The results of the accelerated-ageing tests – aligned with the actual exposure classes – are shown to satisfactorily match the values measured in the case-study.
Finally, the effectiveness of various surface treatments aimed at mitigating environmental damage is discussed and quantified.

2. Experimental program

This research work has two main objectives (a) to experimentally investigate the effect of environmental actions on concrete durability – in both natural and accelerated conditions; and (b) to assess the effectiveness of surface impregnation treatments as a strategy to mitigate the negative effect of environmental deterioration mechanisms.
The experimental program was calibrated on a real case-study, identified through the following criteria: (a) to be representative of architectural concrete heritage with exposed concrete members, both indoor and outdoor; (b) to be located in a typical urban environment; and (c) to be at least 50 years old. The selected building is “Building A”, located in Florence, designed by Leonardo Savioli between 1973 and 1981, known to be one of the most remarkable building in the INA-Casa district of Sorgane (Florence, Figure 1). As a preliminary step, the environmental conditions were assessed by identifying the relevant exposure classes. The outdoor structural elements were found to be mainly at the risk of carbonation-induced corrosion (XC3, XC4) and moderate freezing-thawing (XF1, XF3). Then,

diagnostic tests were performed to characterize the actual concrete in term of mechanical properties, water permeability, carbonation depth and dielectric properties. Material's parameters (in terms of average values and standard deviations) were assumed to be representative of concrete performance 50 years since the construction.
Concrete samples were prepared according to the mix design inferred from the petrographic analysis and the technical documentation.

Figure 1. Sorgane (Florence) - "Building A" (1973-1981): main façade and side views.

Seventy standard samples were prepared, to be later subjected to artificial ageing by means of different processes: carbonation, freeze–thaw cycles, sodium-chloride crystallization, sulfuric-acid attack. The samples were characterized before ageing (i.e., in conditions assumed to be representative of concrete performance in the building site). Later, during the experimental campaign a great number of properties and durability indicators was monitored at increasing ageing cycles, such as: rebound index, modulus of elasticity, compressive strength, near-surface tensile strength by pull-off tests, mass, carbonation depth, capillary-water absorption and dielectric properties.
The values of each parameter in accelerated conditions was compared with the respective average values measured on the existing building. These latter values were assumed to be representative of a 50-years lifetime. The results show that the reduction in terms of durability measured on the building is coherent with the deterioration processes of the samples subjected to carbonation and freeze-thaw cycles, i.e. the accelerated tests are consistent with the exposure classes of the structure in question.
The second objective of this research project is about the possible benefits resulting from the application of surface-impregnation treatments to mitigate concrete weathering, with the focus on an innovative alkoxysilane-based protective treatment.
Furthermore, the effectiveness of different commercial impregnation-treatments aimed at improving concrete resistance to carbonation is the topic of another experimental campaign [4]. The achievement of the second objective highly benefitted from the close interaction with the European Project "InnovaConcrete", focused on the development of innovative materials and techniques [5].

3. Results

An extensive experimental database concerning the evolution of concrete properties with increasing ageing in different accelerated conditions was collected. For instance, Figure 2 shows the effect that different ageing processes have on the mechanical performance of the samples with regard to internal structural damage and concrete near-surface strength. The ageing-related variations of concrete mechanical properties reveal that the worst mechanical decay occurs in the samples subjected to freeze-thaw cycles and salt crystallization. Ageing by carbonation leads to a general slight increase in the concrete strength due to the increased surface hardness. Finally, for the samples submerged in a sulfuric-acid solution there is a *critical immersion time* below which there is no visible internal damage.

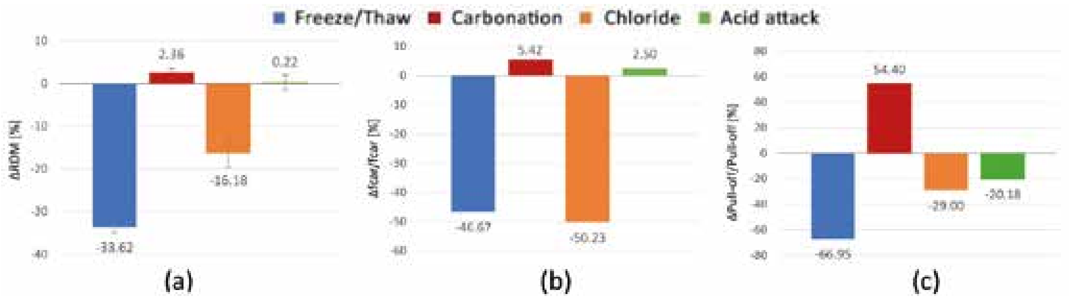

Figure 2. Variation of the mechanical properties of the samples because of ageing: (a) normalized dynamic modulus of elasticity (RDM); (b) compressive strength on cylinders (f_{car}); and (c) pull-off strength.

Based on the test results, the changes of concrete properties measured in the samples subjected to carbonation and freeze-thaw cycles were found to be coeherent with the decrease in durability measured on the existing building. For instance, the average compressive strength of the concrete in the actual structure and the average pulse-transmission speed were reached by the samples after 56 freeze-thaw cycles. Furthermore, ageing by carbonation leads to an increase of the rebound index (Ir) in the concrete, which agrees with the on-site measurements on carbonated-concrete surfaces (Figure 3). Having in mind the conservation issues of architectural concrete heritage, it is worth noting that the application of surface impregnation enhances the substrate resistance, thus limiting the environment-triggered variation in concrete durability properties.

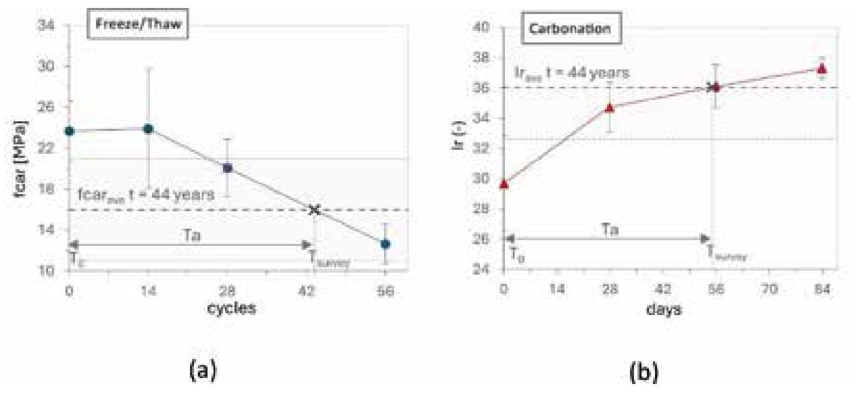

Figure 3. Concrete properties measured during accelerated ageing and average values in the existing building (44-year old): (a) compressive strength (f_{car}); and (b) rebound index (Ir).

4. Concluding remarks and outlook

This research project is about an experimental study where the properties of an ordinary concrete exposed to environmental actions (natural ageing for 44 years; exposure mostly to carbonation

and freeze-thawing cycles) and after accelerated ageing in a lab are compared. Among the major results: (i) assessment of the effects that four accelerated deterioration mechanisms have on the durability-related properties of the concrete; (ii) coherence between the reduction in the durability-related properties measured in the case study (44-year old building subjected to natural ageing) and the deterioration of concrete samples subjected to carbonation and freeze-thawing in a lab; and (iii) reliability of the accelerated test procedure in describing the natural ageing process of a RC building.
Future research will address: (i) the development of a reliable accelerated test procedure; (ii) the investigation on the effect of combined environmental agents; and (iii) the extension of the experimental program to the durability performance of weathered concrete members after strengthening and repairing.

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FRACTURE INSTABILITY IN HEATED CONCRETE: A REASSESSMENT OF THE FUNDAMENTAL MECHANISMS BEHIND EXPLOSIVE SPALLING

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Keywords: fracture mechanics, concrete, direct tensile tests, fire-induced spalling, moisture content, tests on spalling sensitivity

1. Introduction

Concrete is well known for being prone to explosive spalling whenever it is exposed to high temperature, with the projection of concrete flakes and the reduction of the resistant sections. This complex phenomenon is influenced by thermal, mechanical, and hygral factors. The available literature identifies pore pressure and thermal stresses as primary driving mechanisms, that – however – still need a full explanation.
The interaction among these and other mechanisms, as well as the lack of a clear quantitative assessment, make the identification of the parameters governing explosive spalling in concrete a challenging issue. Elastic energy alone cannot justify the explosive nature of the process: the accumulated thermal energy is a supplementary trigger for spalling, together with the water in the pores, which can generate kinetic energy through vaporization. Within this context, a two-stage approach to unravel the intricacies of spalling is proposed:

- **First stage - incipient crack formation:** crack initiation in concrete involves factors such as restrained or loaded sections experiencing thermal expansion [1], mesoscale heterogeneity [2], structural geometry and reinforcement layout [3], and pore pressure [4].
- **Second stage - unstable crack propagation:** a rapid crack propagation and particle projection are involved; the source of the driving energy is the thermal energy accumulated in heated concrete and converted into mechanical work through flash vaporization of the water contained in the thin concrete layers facing the crack [5].

2. Fracture behaviour of concrete

Concrete fracture behaviour is also investigated as it is the basis of the resistance to spalling in its various stages. The direct-tension test is recognized as the most appropriate to evaluate the fracture energy in strain-softening materials, whose behaviour is characterized by several tricky issues concerning – for instance - the axial and flexural stability of the test. Axial stability is impaired by the deformability of the loading frame since the traditional setup comprises rather long columns in compression and the crosshead and the table in bending. The consequent strain energy largely exceeds the dissipative capacity of the specimen to be tested and requires responsive closed-loop control systems to smoothly monitor the descending branch of the test. Concerning flexural stability, several solutions have been proposed to improve the bending stiffness of the test rig, mostly based on ball-bushing guiding systems or adjustable tie-rods secured to the loading platens. The transverse restraint to the specimen, however, may trigger parasitic shear stresses, that cause the propagation of inclined and overlapping cracks.

To address these issues, an innovative frameless test rig is proposed which makes it possible to control the direct-tension tests on notched concrete specimens (Figure 1-left). There is no loading frame, the load is distributed among three parallel actuators and a removable crosshead is utilized to simplify specimen installation. Using this setup not only provides insights into concrete behaviour but also highlights the post-peak differences between high-performance concrete (HPC) and normal-strength concrete (NSC), a crucial aspect in understanding the second stage of spalling (Figure 1-right).

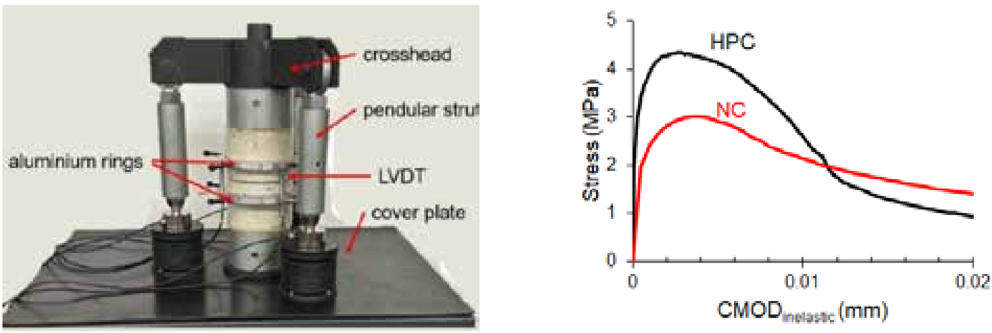

Figure 1. (left) 3ACTION test setup, and (right) different fracture behaviours.

3. Experimental and numerical investigation, results and comments

In the first stage of spalling, the issue is in which way concrete's tensile strength may be exceeded at elevated temperatures. Such an occurrence is due to the combination of the effective stresses from pore pressure and the tensile thermal stresses resulting from thermal gradients, smoothed by transient creep. In Figure 2 the different responses of ultra high-performance concrete (UHPC) mixes are presented during a spalling phenomenon in a lab. These responses are evaluated by means of FEM analyses using the ABAQUS software, where different heating rates are introduced.
Biaxial compressive thermal stresses in walls or tunnel linings cannot be simply added to the hydrostatic pore pressure. Kupfer and Zhukov's failure criteria take care of the pronounced effect that compressive stresses have on tensile resistance. Future research activity should investigate the interaction of biaxial compression and hydrostatic pore pressure, by heating cylindrical sealed specimens in order to create a hydrostatic pressure and by imposing a radial confinement using brushes.

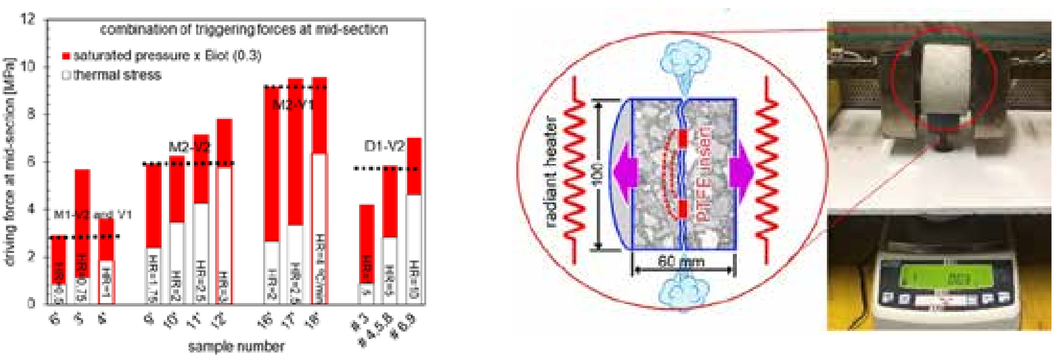

Figure 2. (left) Driving forces in the mid-section of the specimens; and (right) small-scale tests.

With reference to the second stage of spalling, a novel small-scale spalling test has been proposed to explore the parameters influencing this stage, which is accompanied by mass losses and fast crack opening at the onset of instability (Figure 2-right). The crack is forced to initiate inside the specimen (a concrete disk containing a polymeric insert) thanks to the high thermal dilation of the insert. The geometries of the concrete disk and of the polymeric insert were optimized by modelling the whole system via finite elements (ABAQUS software), in order to let the insert generate a crack in the mid-section as soon as the temperature reaches the typical range of spalling.

Figure 3. (left) Intermediate-scale spalling test, and (right) cross-comparison between two different scales.

The effectiveness of the setup versus spalling was investigated through intermediate-scale tests (same concrete mixes, Figure 3). To mitigate any possible excessive natural drying in the curing of small specimens, specific measures were adopted. In this way, the need for intermediate-scale tests was reduced and the optimization of the mixes to have clear-cut spalling phenomena was streamlined. The main findings are:

- The mass losses correlate with crack instability caused by water vaporization.
- The acceleration of the splinters and shards correlates with the pressurization within the crack, where the calculated net pressure approaches saturation.
- Crack initiation timing is crucial, with early and late cracks exhibiting greater stability; concretes with high moisture contents are less prone to spalling; poly- propylene fibres are an effective means against spalling, as they accelerate drying.

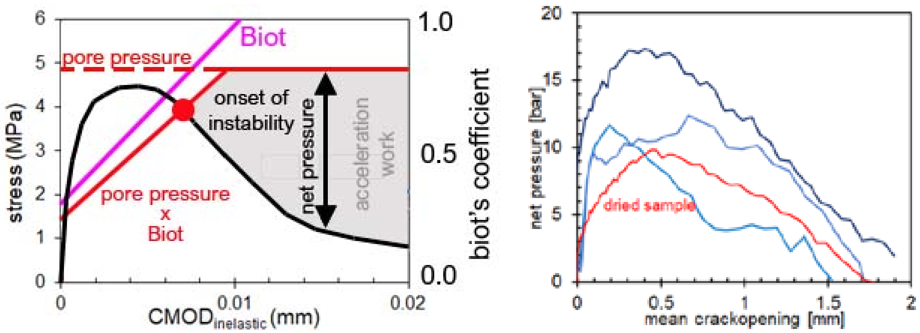

Figure 4. (left) Evolution of the effective pore pressure in two stages; and (right) calculated net pressure from different tests by means of photosensors.

Three processes play a major role concerning the effective stress from pore pressure in the transition between spalling two stages: changes in Biot's coefficient, and flash vaporization + adiabatic expansion + vapour leakage. Biot's coefficient increases as the section gets damaged and cracks. Flash vaporization is also crucial in mitigating the substantial pressure drop by feeding vapour to the incipient crack occurring in the superficial layers. In Figure 4, the crucial moment when the effective pore pressure and section resistance intersect each other is depicted (an indicator of crack instability). The difference between the two lines represents the net pressure, that is close to the saturation pressure in the crack.

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Supervisor: *Professor Roberto Felicetti.*

Topic D

CORROSION

D01 **NICO DI STEFANO** - Assessment of existing bridges with the focus on corrosion

D02 **LORENZO FRANCESCHINI** - A study on existing prestressed concrete beams under chloride-induced corrosion

D03 **ALBERTO STELLA** - Deformation capacity of reinforced-concrete beams: a new perspective for the assessment of sound and corroded members

D04 **NICOLETTA RUSSO** - Effect of cracking and long-term corrosion on the durability of reinforced concrete structures

ASSESSMENT OF EXISTING BRIDGES WITH THE FOCUS ON CORROSION

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Keywords: Bridge Condition Index (BCI), corrosion (in existing RC bridges), tests on corroded RC beams; natural and artificial corrosion; shear strength (of corroded RC beams)

1. Introduction

The collapse of several bridges in the last few years, in Italy and worldwide, indicates that many existing bridges are reaching the end of their life [1-2].
Four hundred bridges in the Province of Brescia (Lombardy, North Italy) have been inspected by the Engineering School of the University of Brescia. By far, most of the inspected bridges (75%) are made of reinforced or prestressed concrete. Among the different forms of degradation found in these structures, reinforcement corrosion is definitely the most common and – probably - the most critical.
The first goal of this thesis is to improve the evaluation of the safety level of existing bridges, starting from the assessment of their state of conservation. The second goal is to better understand the effect of reinforcement corrosion on bridge beams.
The activities carried out by the University of Brescia regarding the inspection and assessment of 400 bridges are described. The database derived from the information collected since 2017 is described and characterized.
A new method for the rating of existing reinforced- and prestressed-concrete bridges is proposed. This method classifies each structure objectively, using a four-level scale, thus automatically defining the repair actions to be taken from minor maintenance work to the closure of the bridge. Special entries also allow to quantify to what extent the corrosion of the rebars may affect the bridge's state of conservation.
Then, two different experimental programs were carried out. The first experimental program was focused on two existing RC bridge beams, about ninety years old, subject to severe natural corrosion.
The second experimental program dealt with five RC beams, which were cast and tested in the laboratory. The stirrups close to the extremities of all the beams, except those belonging to the *control beam*, were subjected to accelerated corrosion, through the application of an electric current.
The aim of the tests was to investigate the effect that natural and artificial corrosion may have on the bearing capacity of the beams, and – in the latter case – on the shear capacity. Few experimental data can be found in the literature on beams with corroded reinforcement and even fewer refer to natural corrosion or to shear.
Finally, an analytical model for the prediction of the shear capacity of RC beams with corroded reinforcement is proposed. It is true that many analytical models are available in the literature, but there is still no general consensus on any of them.

2. Assessment of existing bridges and proposal of a new rating method

The information provided by the inspections and by the subsequent analysis of the design documentation, as well as that resulting from structural investigations, has been implemented into

an extensive database (among the most extensive worldwide), which has allowed to characterize the different types of the bridges. Given the high number of the bridges, the results can be extended at the national level and beyond.
After the in-situ inspection, each bridge was ranked according to a chromatic scale of four colors based on the level of degradation: from green, bridge in good conditions, to red, urgent structural strengthening. The rating of each structure was based on a blind voting procedure involving a 4-member panel of the University of Brescia.
Subsequently, a new method for rating existing RC and PC bridges, with the focus on corrosion, was developed. By filling a form with the information derived from inspections, the method allows to define a reliable and objective rating. At the same time, the method is simple and with an easily understandable physical meaning. Thanks to numerical indicators, including a few specific indicators on reinforcement corrosion, the types of degradation of each bridge can be quantified. It is, therefore, possible to define an overall coefficient of the state of degradation, usually called Bridge Condition Index (BCI) or Bridge Health Index (BHI) [3] in the literature. In this research project, the coefficient is defined as Global Percentage Degradation ("GPD"). The application of the method to a set of 40 bridges made it possible to propose a number of ranges for GPD corresponding to the above-described chromatic classification. The method was finally validated on a total of 153 bridges. Only in 8.5% of the cases, the method led to a class different from the class previously determined from inspection.

3. Experimental and numerical study on corroded RC beams

Two different experimental programs have been carried out.
The first program consisted in two existing RC bridge beams, about ninety years old, subject to severe natural corrosion. The beams are roughly nine meters long with a weight close to 12.5 and 14 tons, respectively. The beams came from a bridge that was dismantled.
For example, Figure 1 shows the experimental curve of N2 ("N2-Test") and the results obtained with the software VecTor2 (developed by Vecchio at the University of Toronto). In VecTor2, both the conditions without corrosion ("N2-VT2-NC") and with corrosion were modelled. In the latter case, corrosion was introduced through either the mean percentage ("N1-VT2-C mean") or the maximum percentage of the bar volume destroyed by the corrosion itself (10.4% in "N1-VT2-C 10.4%").

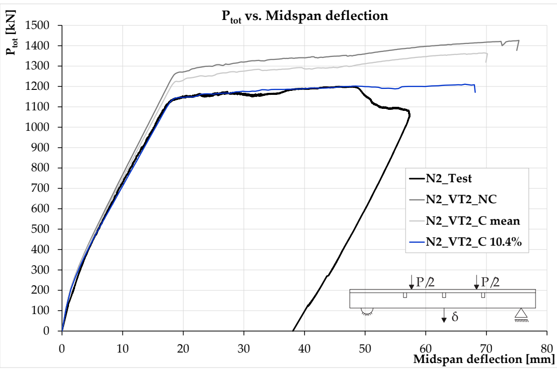

Figure 1. Experimental and numerical load-midspan deflection curves and test set-up.

The interesting result (Fig. 1, left) is that the beam exhibits an ultimate load and an ultimate midspan displacement reduced by about 19% and 31%, respectively, compared to the case without degradation. Moreover, the behaviour of the N2 beam is best represented by the maximum generalized corrosion

of the longitudinal rebars.
The second experimental program was about the effect that corrosion in the stirrups has on shear capacity. Five reinforced concrete beams were made in the laboratory of the University of Brescia. In four cases, the corrosion of some stirrups was accelerated. In the fifth beam, also the longitudinal rebars were partially subjected to corrosion.
From the analysis of the results, the interaction among the different mechanisms that contribute to shear capacity clearly emerges, such as – for instance – the interaction between tension failure and the truss mechanism (Figure 2).
Except in one beam, corrosion always leads to a reduction in both the ultimate load and displacement at midspan. These reductions, however, are indirectly related to the corrosion level as they are primarily related to the variation of the failure mechanisms. The interaction of the various mechanisms is also justified by finite element analysis.
The subsequent characterization of the corrosive process, through specific chemical and electrochemical tests, as well as the quantification of the mass loss (after the tests and the extraction of the corroded bars from each beam), made it possible to accurately identify the type of corrosion.

4. A new predictive model for the shear capacity of corroded beams

Since stirrups are more affected by corrosion than the any other reinforcing device, an analytical model has been formulated to predict the shear capacity of RC members.
Many models in the literature are based on American standards. However, although these models are well established in the engineering practice, they are often at odds with the experimental results concerning non-corroded RC members [4].
For this reason, the model proposed here is based on Model Code 2020. Specific reference is made to the draft 2021/05/09 [5].
The method is applied to 49 tests available in the literature. The analytical and experimental results are in good agreement, as the mean ratio between the experimental and analytical shear capacities is 1.07 (Coefficient of Variation of 17.2%).

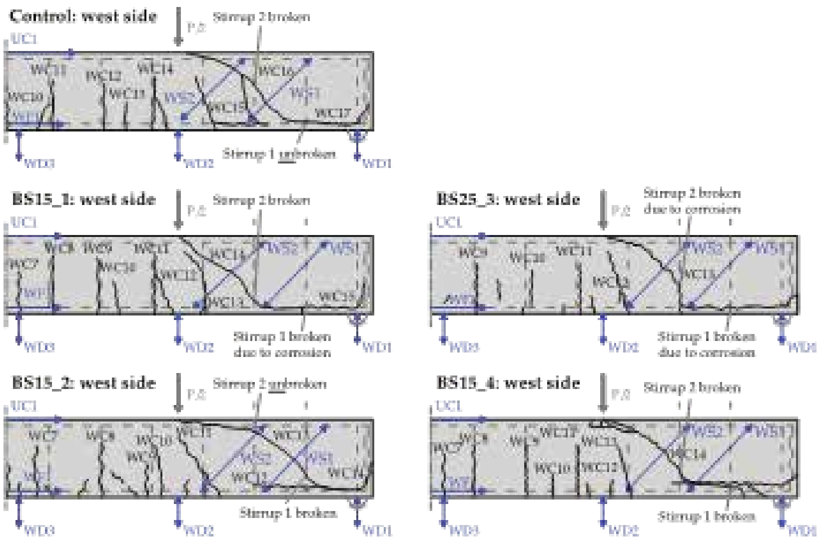

Figure 2. Crack pattern of the beams subjected to accelerated corrosion.

5. Concluding remarks and outlook

The information collected on 400 Bridges in Brescia and in the surrounding region is currently one of the few examples of such extensive databases on bridges.
Compared to more complicated methods, the proposed bridge-rating method appears to be thrifty (as it requires few input data), reliable and objective.
The tests performed in this research project are aimed at improving both the corrosion processes and their structural effects, but further experiments on naturally- and artificially-corroded members are needed.
The proposed model for the evaluation of the shear capacity in RC beams with corroded reinforcement satisfactorily fits some of the many experimental results available in the literature, but a larger number of tests should be considered for a full validation of the model.

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Supervisor: *Professor Fausto Minelli*

A STUDY ON EXISTING PRESTRESSED CONCRETE BEAMS UNDER CHLORIDE-INDUCED CORROSION

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Keywords: prestressed concrete, natural and pitting corrosion, flexural and shear capacity (of corroded PC beams), 3D scanning, residual mechanical behaviour of corroded strands, residual service life.

1. Introduction

Corrosion of steel reinforcements is nowadays considered a major cause of the reduction in both durability and performance in existing reinforced (RC) and prestressed (PC) concrete structures and infrastructures. Moreover, most of the existing heritage has already exceeded its service life and has evident signs of deterioration. The combination of these factors leads to a structural capacity reduction in existing members, often causing unexpected failures due to the lack of bending, shear, or anchorage resistance. Since these failures may result in potential life losses and may have a significant economic impact, corrosion has become a major topic within the scientific community [1].
Although recent experimental, numerical, and analytical studies have been conducted on RC members, the knowledge on PC structures subjected to chloride-induced corrosion is still limited, leaving a number of issues still open to investigation [2]. Firstly, most of the experimental research on the residual structural capacity of corroded members has been performed via artificially-accelerated processes. This technique, however, does not realistically reproduce natural corrosion processes, which require long periods of exposure. Secondly, limited studies have been devoted to the reduction of the structural ductility due to corrosion. Ductility is a particularly relevant parameter of corroded reinforcements since ductility directly influences the structural failure mode that may change from ductile to brittle. Thirdly, there is a paucity of models in the literature concerning the residual mechanical behaviour of corroded prestressing strands [3]. Finally, guidelines and codes on the assessment of the residual service life of corroded structures, are neither complete nor fully validated.
This research project is a contribution to the filling of the above-mentioned knowledge gap, with the focus on: (i) the analysis of the residual structural behaviour of naturally-corroded PC beams, (ii) the proposal of analytical approaches to predict the residual mechanical behaviour of corroded prestressing strands, and (iii) the definition of a simplified analytical model to predict the residual service life of PC beams subjected to chloride-induced corrosion.

2. Experimental programme and analytical models

Three are the main sections of this research work. First, several naturally-corroded PC beams subjected to 10 years of sea water wet-dry cycles are investigated in order to evaluate the influence of corrosion on their residual structural performance. Prior to testing the beams in 3- and 4-point bending, the surface defects of each corroded PC beam were analysed and later Digital Image Correlation (DIC) was used to investigate the displacement and strain fields. Secondly, analytical constitutive laws, named CPS- and SCPS-model (*/**), were formulated for the prediction of the residual mechanical behaviour of corroded prestressing strands. To this aim, after the mechanical tests, the beams were dismantled and twenty-four prestressing strand samples were extracted to be further analysed. Then, 3D images of retrieved un-corroded and corroded strand samples were obtained by using a structured light 3D scanner. The spatial variability (in the sections

and along the axis) of pitting was later investigated by superimposing the un-corroded and corroded 3D images using the GOM (***) Inspect software, Figure 1. Finally, tensile tests were performed for the calibration of the numerical models and a comprehensive database was collected for their validation. Thirdly, an analytical approach for evaluating the residual flexural and shear capacity of corroded PC beams was proposed based on equilibrium and compatibility conditions, by adopting a single input parameter, i.e. the maximum penetration depth of the most corroded wire. The model quantifies the prestressing losses and the residual mechanical properties of the strands, evaluates the corrosion parameters, updates the transmission length and takes care of the long-term reduction of the bond strength.
It is worth noting that this research project took advantage of the close collaboration with the Politecnico di Torino and the Instituto Eduardo Torroja of Madrid.

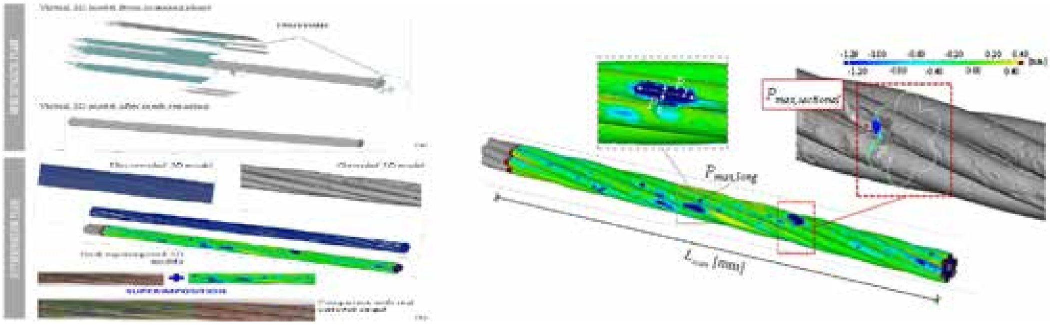

Figure 1. GOM Inspect analysis: (a) superimposition of corroded and un-corroded 3D models and (b) study of main corrosion parameters.

3. Results

The surface defects play a key role in the corrosion process of the prestressing strands and in the subsequent residual structural performance of corroded PC beams. Indeed, the increase in the corrosion level and the crack pattern development during the service life, strongly influence the load-carrying capacity, the deflections, and the failure mode of pre-tensioned PC beams, which turns from ductile to brittle. In detail, two distinct transitional behaviours were identified in the corroded PC beams under increasing corrosion levels: (i) a ductile-brittle transition associated to the deterioration of the flexural nonlinear behaviour of corroded beams (Figure 2a), and (ii) a ductile-brittle transition associated to the change in the failure mode from bending to shear (Figure 2b) [4].

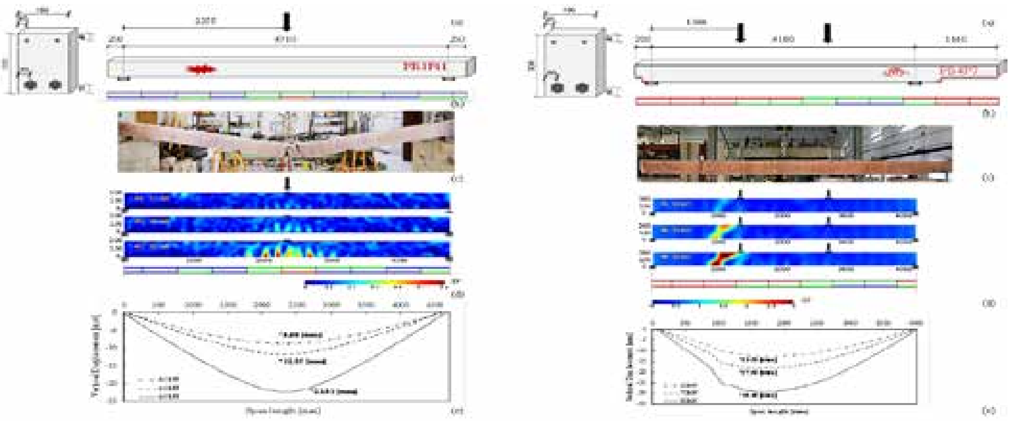

Figure 2. Corroded-beam failure modes: (a) in bending, and (b) in shear.

Based on pitting spatial variability and on the tensile tests, two constitutive laws (indicated as CPS- and SCPS-models) were proposed to predict the stress-strain relationship of corroded strands [5].

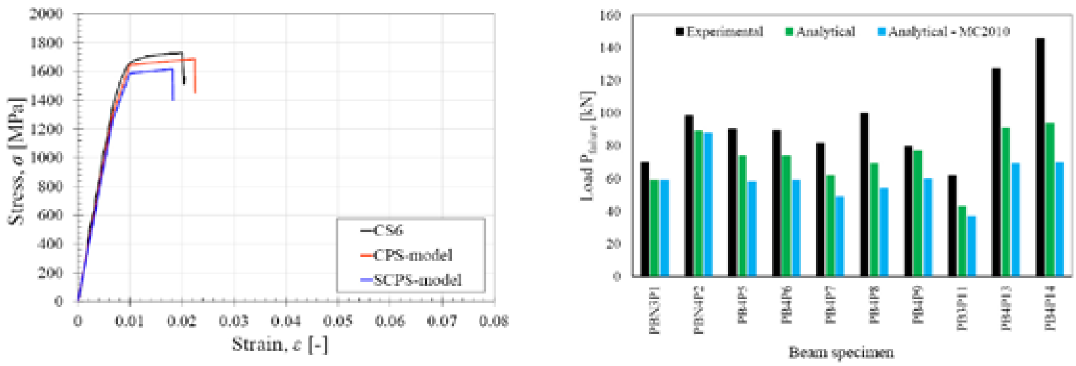

Figure 3. (a) Stress-strain analytical predictions for a corroded strand, and (b) ultimate loads of corroded PC beams from the tests, MC2010 and the proposed method.

The models, whose accuracy and effectiveness were validated by comparison with test data, are based on the *equivalent spring material approach* that reproduces the overall response of a corroded strand as the sum of the contributions of the wires, which act like springs working in parallel, Figure 3a. The refined CPS-model assumes the cross-sectional loss of each wire as the main input parameter for the prediction of the ultimate strength and the ultimate strain decay, and considers different decay laws as a function of three pit configurations [6]. The SCPS-model, that is a simplified version of the CPS-model, was designed for daily engineering practice, since it is based on a single input parameter, i.e. the maximum penetration depth of the most corroded wire. This model is independent from pit morphology and adopts a single relationship for the ultimate strain decay [7]. Last but not least, a preliminary partial safety factor $g_{m,corr}$ for the design strength of corroded strands is determined following a probabilistic estimation of the SCPS-model uncertainties.
Based on the SCPS-model, the simplified analytical model proposed in this study for the service-life of corroded PC beams has been successful in predicting the ultimate load and failure mode of the investigated beams (Fig. 3b). Although fairly conservative, the proposed approach is a step forward compared to available standards.

(*/**) CPS/SCPS = Corroded/Simplified Corroded Prestressing Strands model.
(***) GOM = German Association for Optical Instrumentation.

4. Concluding remarks and outlook

In the present work, the issue of chloride-induced corrosion is investigated. To this end, the results of a comprehensive experimental campaign are presented, and analytical relationships are formulated. As a result, useful constitutive laws for the prediction of the reduced mechanical response of corroded strands are proposed, as well as an analytical approach for the assessment of the residual life of corroded PC beams, to the advantage of daily engineering practice.
The residual structural performance of corroded PC members under dynamic and cyclic loading, the corrosion-induced debonding of the strands, and the applicability of the proposed approach to post-tensioned reinforcement and in different environmental conditions are among the issues still open to investigation.

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Supervisor: *Professor Beatrice Belletti*

DEFORMATION CAPACITY OF REINFORCED-CONCRETE MEMBERS: NEW INSIGHTS FOR THE ASSESSMENT OF SOUND AND CORRODED BEAMS

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Keywords: RC beams, deformation capacity, ductility, rebar corrosion, deformation demand, ground settlements, structural monitoring, DInSAR* techniques

1. Introduction

Deformation capacity is a fundamental requirement for reinforced-concrete (RC) members of certain building and infrastructure typologies, especially in order to resist the inelastic deformations induced by strong seismic events or differential ground settlements [1], [2]. The necessity of having effective and reliable methods for the practical evaluation of both the deformation capacity and demand in RC members has risen over the past decades, all the more because the design codes are progressively adopting performance-based design criteria for the design of new structures, as well as for the assessment of existing structures.

Several issues are still open to investigation like the evaluation of the deformation capacity, especially in existing RC structures, which may also be affected by degradation phenomena such as reinforcement corrosion.

On the other hand, several uncertainties are still affecting the practical assessment of the actual deformation demand of RC members. As an example, in the case of differential ground settlements, even fundamental data - such as the entity and distribution of the settlements – can hardly be accurately quantified.

This research work is aimed at addressing some of the above-mentioned knowledge gaps, with the focus (a) on the modelling approaches to evaluate the deformation capacity, and (b) on the potential and limitations of a recently-introduced monitoring technique aimed at improving the evaluation of the deformation demand in case of differential ground settlements.

Four are the core chapters (Figure 1). In the first, a general analytical formulation for the failure mode and ultimate curvature of RC beam sections is proposed. In the second chapter, an experimental campaign on sound and corroded beams is presented, whose results are later used for validation purposes. In the third chapter, the analyses performed to check the modelling performance of the proposed analytical formulation are presented, together with a design-oriented numerical strategy for structural modelling. In the fourth chapter, the use of recent DInSAR* techniques [3] is discussed, as an aid in monitoring settlement-induced deformations.

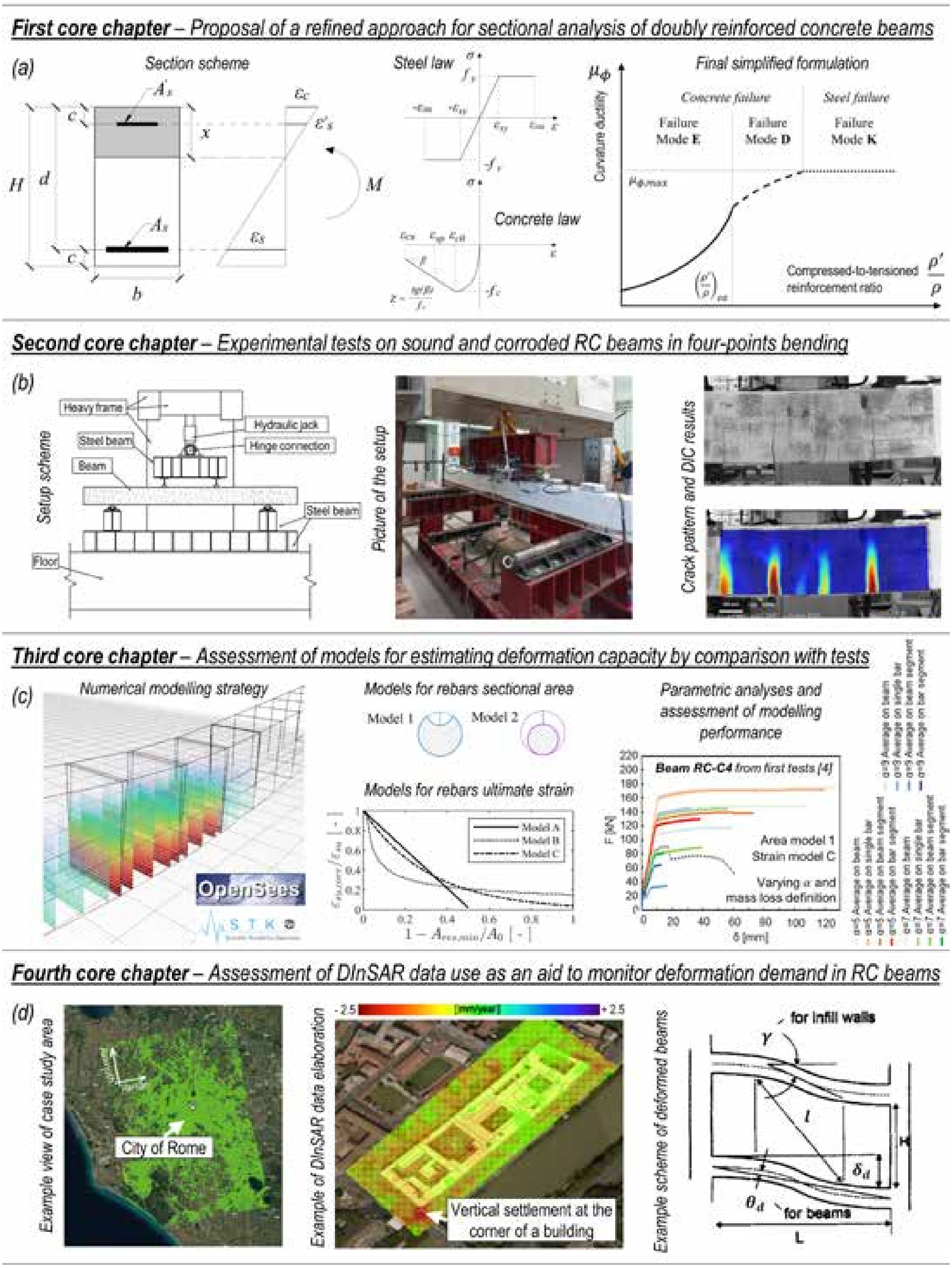

Figure 1. Core chapters, methodologies and example of the results of this research project on the deformation capacity and demand of sound and corroded RC beams: (a) proposed general analytical formulation for sectional analysis; (b) 4-point bending tests; (c) validation of the proposed analytical and numerical approaches using experimental data on sound and corroded beams; and (d) use of DInSAR* data as an aid in monitoring the settlement-induced deformation demand in RC structures (latter figures adapted from [2,3]).

2. Methods

The model of Figure 1a was developed as a set of closed-form analytical equations for the identification of the failure mode and the quantification of the ductility in doubly -reinforced concrete beams. The aim was to introduce improvements with respect to the traditional approaches, e.g., by considering the various failure modes of the reinforcement, including cover spalling.

A recent experimental campaign [4] was the starting point (a) to analyze the effect that longitudinal bar corrosion may have on the flexural response of RC beams, and (b) to check the performance of the proposed modelling approach. In addition, new tests on two severely-corroded beams from the same batch (Fig. 1b) were performed in collaboration with the University of Rome "Tor Vergata", to extend the data base and to test other measurement techniques like digital image correlation - DIC.

The proposed analytical approach (Figure 1a) and a design-oriented numerical- modelling strategy based on fiber models and developed within OpenSees and STKO, were used to model the beams of the test campaign [4]. An in-depth parametric analysis was performed considering different models for corrosion (Figure 1c [5–7]). The new tests (Figure 1b) were used to validate the numerical results of the first tests.

The applicability of DInSAR* data to structural monitoring [3] and to assess the deformation demand was checked by using COSMO-SkyMed data for a case-study area close to Roma, Figure 1d, provided by the Italian Space Agency (ASI) within the Project DPC-ReLUIS 2019-2021-WP6. Several sets of data were processed.

3. Results and contributions

The proposed formulation is shown to be effective in realistically predicting the failure modes of sound and corroded beams, and has been used to check the detailing rules for local ductility in the Italian and European standards. Critical points (mainly related to the assumptions concerning the failure modes) have been detected and solutions are proposed, as a contribution to project DPC-ReLUIS-2019-2021-WP11 [8].

The data from corroded beams show that, in case of pronounced pitting corrosion, the definition of the volume of the spatial domain used to compute the average mass loss can markedly affect the value of the mass loss [4], [9]. Though often neglected in the past, this aspect is quite relevant, especially whenever the issue be to propose a law relating corrosion damage (e.g., maximum pit depth) to mass loss.

The numerical modelling strategy is effective in capturing the residual capacity of corroded beams. However, depending on the specific model adopted in the description of corrosion damage, the results can be very different [9]. Moreover, the commonly-suggested pitting factor $\alpha = 10$ is shown to severely underestimate the capacity of most corroded beams, when the mass loss is computed locally. In such cases, values in the range $\alpha = 5$-7 seem to be more appropriate (α should be chosen based on corrosion level). The severe bond losses at high corrosion levels may even have a marked influence on structural response.

The elaboration of DInSAR* data for the case-study area highlights the potential and the challenges [3], of the proposed approach to structural assessment, something that has been taken care of in the draft of DPC-ReLUIS guidelines [10]. Some of the challenges are: data accuracy, data availability from satellites, and whether or not the monitored period should include the starting time of ground deformation processes.

4. Conclusions and outlook

The approaches aimed at evaluating the deformation capacity and demand of RC members are becoming increasingly relevant as performance-based design is more and more extensively adopted, and many are the challenges offered by existing deteriorated structures. Testing and modelling RC beams, and using innovative monitoring techniques may improve the assessment techniques also from the point of view of engineering practice, as shown in this thesis.

Open issues are the refinement of the measuring techniques and of the models concerning the effect that local corrosion may have on the reinforcement, as well as the integration of DInSAR* data with the information coming from on-site monitoring.

(*) DInSAR = Differential Interferometry Synthetic Aperture Radar.

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EFFECTS OF CRACKING AND LONG-TERM CORROSION ON THE DURABILITY OF REINFORCED-CONCRETE STRUCTURES

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Keywords: reinforced-concrete durability; cracked concrete; reinforcement corrosion; carbonation; chlorides; morphology of corrosive attacks; sectional losses; steel-concrete interface; mineralogy (of corrosion products).

1. Introduction

Corrosion of steel reinforcement is one of the main causes of premature degradation and failure in reinforced concrete structures [1]. Over the last few decades, based on many studies on corrosion in concrete, several models have been developed to predict the long-term evolution of corrosion. Though these models are used in the design stage to guarantee structural durability, some issues concerning their applicability are still open to investigation. For instance, concrete cracking is not considered, even if cracking is almost inevitable in real structures. National and international structural codes introduce limitations on crack width, in the order of magnitude of several hundreds of micrometres, *e.g.* 200-400 µm depending on the exposure class according to NTC 2018 (Italian Technical Norms on Constructions [2]), even if thinner microcracks (< 100 µm) may have significant effects on concrete durability. Moreover, while a deeper knowledge is available on the variables involved in the initiation of corrosion, there is still an ongoing debate on the processes that occur and influence the long-term propagation of natural corrosion [3], since short-term experimental campaigns can hardly shed light on these processes.
The aim of this research is (a) to quantify the effects of cracking on concrete durability-related performance and on corrosion behaviour of steel reinforcement (considering both chloride-induced and carbonation-induced corrosion), and (b) to perform a multiscale, morphological and mineralogical characterization of long-term reinforcement corrosion, taking advantage of the availability of old laboratory specimens (a rare occurrence!).

2. Experimental program

In the first part of the experimental program, the effect of cracking on concrete durability was assessed. Load-induced micro-cracks (width between 10 µm and 100 µm), different cement types (Portland cement - OPC, Portland-limestone - PLC and pozzolanic - PC), and w/c ratios (0.45 and 0.55) were considered. The resistance to carbonation penetration was investigated through accelerated carbonation (Acc) after different exposure periods, while chloride penetration resistance was studied trough accelerated tests (RCM, after different curing periods), and conventional medium-term tests (i.e., by immersion - Imm, after different exposure periods), followed by either titration technique (T) or colorimetric technique (C). The initiation and propagation of chloride-induced corrosion were investigated in five uncracked specimens and in ten longitudinally-microcracked specimens, made of PLC cement (w/c 0.45), reinforced with carbon-steel bars and monitored by means of electrochemical measurements.

The propagation of long-term natural corrosion was studied during a research stay at TNO (Delft, NL). Specimens were made with different cement types (OPC and a blast furnace cement - BFC), initially subjected to either accelerated carbonation or penetration of chlorides. After the initiation of corrosion, the specimens were left under unsheltered outdoor environmental conditions for more than 20 years. Corrosion was characterized at multi-scale levels by a combination of different techniques, among which non-destructive electrochemical measurements, and - after the removal of the reinforcement - X-ray computed tomography (CT-scan) followed by image analysis, to visualize the distribution and the extension of corrosive attacks, and to evaluate sectional losses.

3. Results

The effects of cracking were evaluated through the increase in carbonation coefficient and chloride diffusion coefficient in cracked concrete with respect to uncracked conditions (K_{cr}/K_{uncr} and D_{cr}/D_{uncr}, respectively). The micro-cracks considered in this study, caused an increase in carbonation coefficient up to 4 times in concretes with w/c 0.45 (Figure 1a). The highest increments in chloride diffusion coefficient were recorded after immersion test, through colorimetry (up to 10 times).

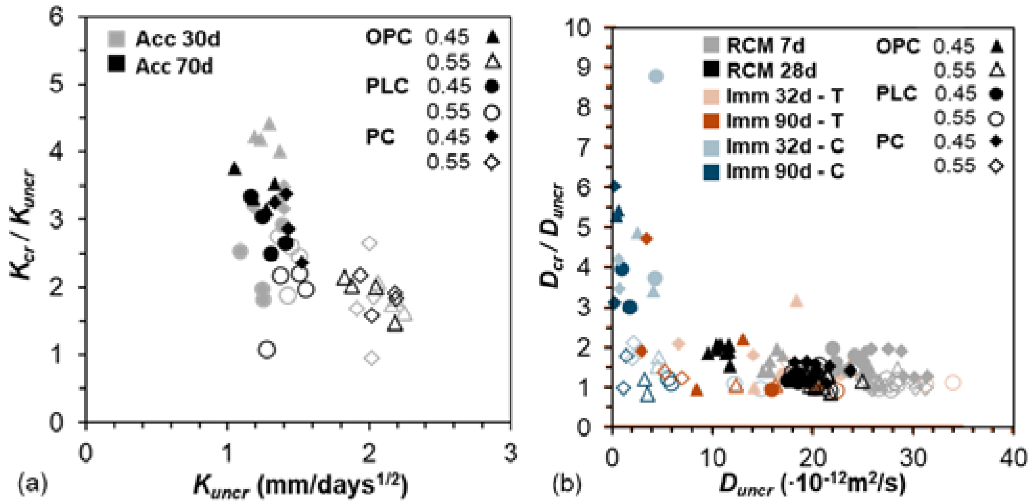

Figure 1. Effects of micro-cracking on the resistance (a) to carbonation penetration (accelerated tests), and (b) to chloride penetration (various tests, after different exposure periods); d = days.

The effects of cracking on the acceleration of the penetration of both carbonation and chlorides depended on the adopted procedure. However, the more impervious the concrete, the more pronounced the penetration. Furthermore, the increase in carbonation or chloride penetration was never found to be a function of crack width and depth.

For chloride-induced corrosion, the initiation time was reduced to zero in those specimens where cracking was extended to the entire bar cover. Conversely, comparable initiation times (Figure 2a) were detected in both uncracked and slightly cracked specimens (grey and red histograms). No effects of micro-cracks were recorded on corrosion rate (Figure 2b), but the rebars in cracked carbonated concrete reached i_{corr} values one-order-of-magnitude higher (dotted symbols), implying a drastic reduction in the propagation time.

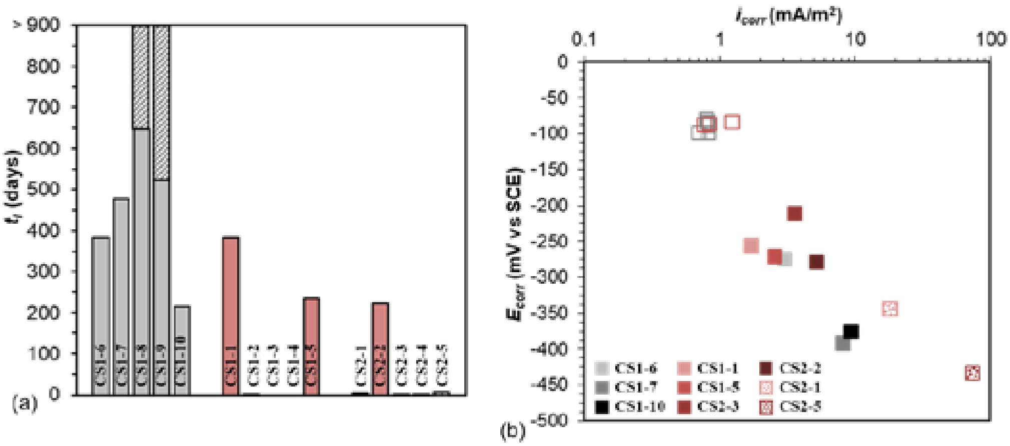

Figure 2. (a) Corrosion initiation time (t_i) in uncracked and cracked specimens reinforced with carbon steel bars; and (b) average values of E_{corr} and i_{corr} before (hollow symbols) and after (solid symbols) corrosion initiation (grey = uncracked, red = cracked).

As an example of the results obtained in the second phase of this research project, Figure 3 shows the X-ray CT-scan of three rebars, with their sectional losses (trend along the length of the rebars and average values in red). After 22 years of natural corrosion, negligible sectional losses were detected in the specimens subjected to carbonation-induced corrosion. Considering chloride-induced corrosion, the OPC specimen exhibited the most advanced state of corrosion that was detected by means of electrochemical measurements (corrosion potential and corrosion current density), as confirmed by CT-scan (average sectional losses close to 7% with peaks up to 12%). The rebar in the BFC specimen exhibited an intermediate corrosion level (electrochemical measurements; average sectional losses close to 3% evaluated via CT-scan). Interestingly, the BFC specimen exhibited severe corrosion-induced cracking, while the OPC specimen was characterized by abnormal macro-porosity in the cement paste, that made it possible for the corrosion products to expand and prevented concrete cracking, completely overshadowing the severe corrosion state.

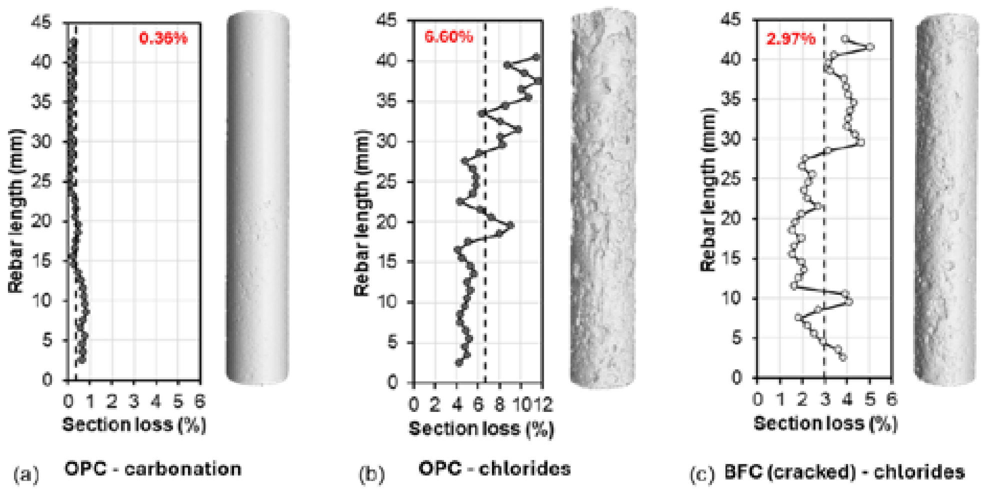

Figure 3. Evaluation of the sectional losses and rebar reconstruction from CT-scan, for (a) OPC concrete subjected to carbonation-induced corrosion, (b) OPC concrete subjected to chloride-induced corrosion, and (b) BFC concrete subjected to chloride-induced corrosion.

4. Concluding remarks and outlook

The experimental results obtained in this research project on both chloride-induced and carbonation-induced corrosion, indicate that the effects of pre-existing cracks (even much thinner than those commonly accepted by structural codes) are more severe in more impervious concretes, especially when such cracks propagate through the entire bar cover. Direct consequences are an acceleration in the penetration of chlorides and carbonation, reducing (in some cases drastically) both corrosion initiation and propagation times. As for the experimental results on long-term propagation of corrosion, chloride-induced corrosion rate (measured through non-destructive electrochemical techniques) is clearly correlated to the average sectional loss (evaluated through CT-scan after the removal of the bar). Further analyses and tests, however, should be performed to verify this correlation. The severe corrosion detected in one case (with a rebar embedded inside uncracked concrete without external rust stains) indicates that the visual inspections typically performed on existing structures may not be sufficient to detect severe corrosion, as the specific conditions of the cement paste and of steel-concrete interface should be taken into consideration.

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Judgements of the Board of Examiners
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Lorenzo Franceschini

A Study on Existing Prestressed Concrete Beams under Chloride-Induced Corrosion

La tesi affronta il tema della capacità residua di travi in cap soggette ad un naturale processo di corrosione delle armature di precompressione indotta da cloruri, proponendo approcci analitici per valutare la capacità residua dei cavi e la vita residua delle travi.

Di grande rilevanza è l'attualità del tema, con particolare riferimento alle strutture da ponte, ed estesa è la sua trattazione, in quanto la ricerca adotta un ampio approccio di tipo numerico-sperimentale. La parte sperimentale non si limita ad indagare il comportamento delle travi, ma si spinge fino allo studio dei cavi estratti, mentre la parte numerica è finalizzata all'interpretazione dei risultati.

Ad attualità ed ampiezza di trattazione si accompagnano l'ottimo inserimento nel contesto tecnico-scientifico, la notevole rilevanza scientifica - che scaturisce dall'approccio teorico-sperimentale adottato – e la diretta applicabilità dei risultati in campo progettuale, per la valutazione della capacità portante delle opere esistenti.

Lucia Licciardello

Structural Behaviour of Extruded 3D-Printed Concrete Members

La tesi riguarda l'ambito di grande attualità delle strutture realizzate mediate strategie costruttive innovative digitali, per le quali la caratterizzazione del materiale stratificato richiede prove complesse e specifica normativa, anche al fine di formulare adatti modelli computazionali.

Viene affrontato il tema della stampa tridimensionale di elementi in conglomerato cementizio, proponendo una metodologia di prova per la valutazione delle proprietà dei materiali adatti alla stampa 3D e studiandone il comportamento strutturale attraverso la realizzazione di pareti con cavità, per le quali viene anche formulata una modellazione analitica.

Accanto alla grande ampiezza della trattazione – basata su un innovativo approccio di tipo analitico-sperimentale – rilevante è l'inserimento nel contesto tecnico-scientifico (tuttora in grande evoluzione), cui la tesi contribuisce sia sotto l'aspetto scientifico, che progettuale, quest'ultimo esposto però alla formidabile sfida presentata dall'inserimento delle armature.

Nicoletta Russo

Effects of Cracking and Long-Term Corrosion on the Durability of Reinforced-Concrete Structures

Scopo della ricerca è la quantificazione degli effetti della fessurazione sulla durabilità del calcestruzzo e sulla corrosione delle armature, ambiti di grande attualità per le molte strutture esistenti in uno stadio avanzato della loro vita utile.

Il tema della corrosione delle armature viene affrontato attraverso la caratterizzazione multiscala, morfologica e mineralogica del processo corrosivo a lungo termine, traendo vantaggio dalla preziosa disponibilità di vecchi campioni d'armatura residui di prove di laboratorio e richiedendo nel contempo complesse metodologie di indagine.

La trattazione appare ampia, organica e completa, ben inserita nel contesto tecnico-scientifico e con potenziali ricadute progettuali. I risultati rappresentano un significativo contributo ad una migliore comprensione dei fattori di degrado che influenzano la durabilità strutturale.

HONORABLE MENTIONS
MENZIONI DI MERITO
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Alessio Rubino

A Fracture-Mechanics Approach for the Design of Fibre-Reinforced and Hybrid Reinforced Concrete Structures

Interessante ed attuale studio di tipo numerico sul quantitativo minimo di fibre metalliche (in presenza o meno di armatura tradizionale) atto a garantire la duttilità alla prima fessurazione in travi inflesse. La modellazione si basa sulla meccanica della frattura lineare ed ha importanti ricadute progettuali. Lo studio è esteso e articolato, ben inserito nel contesto tecnico-scientifico e foriero di nuovi dati utili per la comprensione della fisica del fenomeno.

Klajdi Toska

IInnovative techniques for monitoring and strengthening existing structures: fabric-reinforced cementitious composites for the confinement of RC structures

La tesi – di grande attualità tecnico-scientifica e ben inserita nel proprio contesto – riguarda la riabilitazione strutturale di opere in calcestruzzo armato mediante l'uso di compositi cementizi fibrorinforzati. L'obiettivo – raggiunto per via teorico-sperimentale - è di aumentare le conoscenze sul comportamento delle membrature confinate ed incamiciate, e di sviluppare una legge costitutiva per il calcestruzzo confinato con compositi cementizi fibrorinforzati.

Eleonora Grossi

A Novel 2D Dissipative Connection for the Seismic Retrofit of Precast Structures: Conceptualization, Prototyping, Mechanical Characterization and Numerical Modelling

La tesi riguarda una innovativa connessione dissipativa metallica multistrato per l'adeguamento sismico di edifici esistenti a telaio. La connessione viene studiata sperimentalmente e modellata analiticamente in presenza di sisma mono- e bi-direzionale, con potenziali ed interessanti ricadute nella progettazione antisismica. La trattazione numerico-sperimentale è ampia e ricade in un contesto tecnico-scientifico molto attuale.

Editorial Note/Nota degli Editori

For editorial reasons, some of the titles of the dissertations have been slightly modified to make them simpler and/or more efficacious. For the sake of completeness, the original titles (before the modifications) are listed below.

Per ragioni editoriali, alcuni dei titoli delle tesi sono stati leggermente modificati per renderli più scorrevoli e/o più efficaci. Per completezza, i titoli originali (prima delle modifiche) sono riportati nel seguito.

Nico Di Stefano	Assessment of existing bridges with special emphasis on corrosion.
Lucia Licciardello	Study on the structural behaviour of 3D printed concrete elements made by extrusion process.
Stefano Giuseppe Mantelli	Influence and on-site assessment of long-term prestressing losses on shear strength of bridge girders.
Carmine Molitierno	Pseudo-dynamic tests for seismic performance assessment: infrastructure development, verification and test reliability.
Marco Carlo Rampini	Glass fabric-reinforced cementitious mortar (GFRCM) composites: strengthening and retrofitting of existing reinforced-concrete structures.
Vincenzo Romanazzi	Design, mechanical and structural characterization of sustainable and high-performance concrete.
Nicoletta Russo	Effects of cracks and long-term corrosion propagation on reinforced-concrete structures durability.
Klajdi Toska	Innovative techniques for monitoring and strengthening existing structures: confinement through FRCM composites of reinforced-concrete structures.

Innovation in Concrete Structures and Cementitious Materials - 2024

Editors Luigi Coppola and Pietro G. Gambarova

The long summaries of the doctoral dissertations defended in Italy in the period 2021-24 are presented in this volume with the focus on structural cementitious composites, reinforced-/prestressed-concrete construction and structural design. As in the previous 4 volumes (2014, 2016, 2018 and 2021), the objective is to improve the mutual understanding between construction industry, cement producers, professionals engineers, architects and materials experts on the one hand, and researchers on the other hand, by facilitating the two-way flow of information between academy and practice.

I sommari estesi delle tesi di dottorato discusse in Italia nel periodo 2021-24 vengono presentati in questo volumetto con riferimento ai conglomerati cementizi strutturali, alle costruzioni in calcestruzzo armato e precompresso, ed alla progettazione. Come nei precedenti 4 volumetti (2014, 2016, 2018 e 2021), l'obiettivo è di accrescere la comprensione reciproca fra industria delle costruzioni, produttori di cemento, ingegneri progettisti, architetti ed esperti dei materiali da un lato, e ricercatori dall'altro, facilitando il flusso bidirezionale delle informazioni fra accademia e pratica.