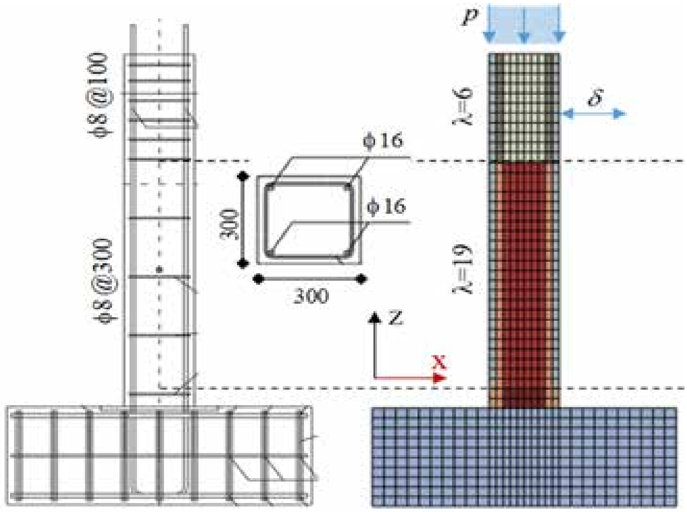
ACI Italy Chapter - Federbeton Awards

INNOVATION IN CONCRETE STRUCTURES AND CEMENTITIOUS MATERIALS – 2020



MADE EXPO MILANO NOVEMBER 22-25 2021

Summaries of the PhD Dissertations defended in Italy in the years 2019 and 2020

Editors
Luigi Coppola and Pietro G. Gambarova

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Innovation in Concrete Structures and Cementitious Materials

November 22-25, 2021 – MADE expo, Milan

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Talent hits a target no one else can hit
Genius hits a target no one else can see
(Arthur Shopenhauer, 1788-1860)

Never regard study as a duty, but as
an enviable opportunity to learn
(Albert Einstein, 1879-1955)

Front photograph from the thesis "Crack Model for the Capacity Assessment of RC Structures using Nonlinear Finite-Element Analysis within the Framework of PARC Software" by Francesca Vecchi, University of Parma.

Foreword

For the fourth time since 2014, Federbeton - Italian Association of Cement Producers - is offering the PhD graduates (academic years 2018-19 and 2019-20) three awards in recognition of the best dissertations on cementitious materials and reinforced-/prestressed-concrete structures. As in previous occasions, 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 MADE expo 2021 helps in meeting the previous objective.

Before introducing the long summaries, we should remember the teachings of the last three years, that started with the collapse of the Polcevera Viaduct (August 2018, Genua, Italy) – a prestressed-concrete architecturally-valuable structure, flawed by a complex technology and a demanding maintenance since its opening in the mid-sixties – and ended with the opening of the new San Giorgio Viaduct (August 2020) – a composite steel-concrete structure characterized by graceful and simple lines, and definitely less maintenance hungry.

In the last few years, the frequency of extreme events mostly related to climate change has grown dramatically, with very extended natural fires to the detriment of buildings and infrastructures, and torrential rains to the detriment of bridge safety. Also the accidents during the repairing/refurbishing/strengthening of existing buildings and the construction of new buildings are on the rise. The fire in the roof of Nôtre Dame (Paris, April 2019) is a recent example concerning historical and monumental buildings, while the local fire erupted in the large department store “Souks” under construction in Beirut (September 2020) designed by Zaha Hadid is a further demonstration of the risks run during the construction and completion phases.

Fires and earthquakes (that often start fires) share (a) the involvement of the whole structural behavior with its design- and/or construction-related flaws, and (b) the necessity of structural repairing/refurbishing/strengthening, where a critical role is played by innovative cementitious composites. These materials are the subject of several of the dissertations summarized in this volume. Needless to say, however, beside the structural materials, conceptual design, management – based on load monitoring – and maintenance are of the utmost relevance to guarantee the desired long-term structural performance.

Most of the above-mentioned issues are addressed in the twenty PhD dissertations defended in the last two years. The total number is similar to that of the period 2012-

18 (average of eleven dissertations per year), but the pandemics has certainly forced some PhD Candidates to postpone the defense of their dissertations.

The 20 long summaries received by the committee come from 15 Italian universities, in two cases in cooperation with foreign universities. More than 1/3 of the dissertations is dedicated to materials, while a little less than 2/3 deals with structural applications and innovative technologies. In detail:

- 25% (5) is focused on innovative cementitious composites (multifunctional concretes, non-cementitious binders, recycled aggregate, workability, fibers);
- 35% (7) is about RC and PC constructions (repairing and strengthening via external structures, or concrete layers containing vegetable or inorganic fibers; mixed masonry-concrete members; nonlinear numerical modelling; testing of tunnel segments and structural anchors);
- 25% (5) deals with extreme conditions (seismic and cyclic loads, fire and chemical corrosion) and damage control in structural members;
- 15% (3) considers innovative technologies (3D concrete printing from the points of view of technology, cementitious materials and characterization of the adhesion between contiguous layers and filaments).

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 (hardly an easy task!), eight summaries (40% 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 as an Academy-Industry "bridge" by all people interested in Civil/Building Engineering and Structural Materials.

<u>Board of examiners</u>
Luigi Cedolin, Ezio Giuriani, Pietro G. Gambarova (ACI – Italy Chapter), Roberto Realfonzo (ACI-Italy Chapter) and Michela Pola (Federbeton)

<u>Editors of this volume</u>
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Premessa

Per la quarta volta a partire dal 2014 Federbeton (Associazione dei Produttori di Cemento) offre ai neoDottori degli anni accademici 2018-19 e 2019-20 - tre premi per le migliori tesi di dottorato sui conglomerati cementizi e sulle strutture in calcestruzzo armato o precompresso. Come nelle precedenti occasioni del 2014, 2016 e 2018, 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.

Prima di introdurre il volume, è però doveroso richiamare gli insegnamenti di questo ultimo triennio, che è iniziato con il collasso del Viadotto sul Polcevera (Agosto 2018) – opera in calcestruzzo precompresso degli anni sessanta, di grande impatto architettonico, ma tecnologicamente complessa e di difficile manutenzione – ed è terminato con l'inaugurazione del nuovo ponte "San Giorgio" (Agosto 2020) – opera mista in acciaio e calcestruzzo, elegante nelle sue linee essenziali e certamente di più facile manutenzione.

Questi ultimi tre anni hanno visto anche l'aumentare di frequenza di eventi estremi in gran parte legati agli indubbi cambiamenti climatici, con vastissimi incendi di foreste e danni ad edifici ed infrastrutture, e piogge torrenziali con danneggiamento e crollo di ponti. Tuttavia sono in aumento anche gli incidenti legati alla ristrutturazione /adeguamento/rafforzamento di edifici esistenti ed alla costruzione di nuovi edifici. L'incendio della copertura di Nôtre Dame è un esempio molto recente in tema di edifici storici e monumentali (Aprile 2019), mentre il principio di incendio nel grande centro commerciale in costruzione "Souks" di Beirut (Settembre 2020) – su progetto di Zaha Hadid – è emblematico dei rischi in fase di costruzione o completamento.

Incendi e terremoti – spesso loro stessi causa di incendio – sono accomunati dal mettere in discussione l'intero iter progettuale e costruttivo, fino ad arrivare alle misure di ripristino e rinforzo, ove ampio è lo spazio per i materiali cementizi innovativi oggetto di parecchie delle tesi citate in questo volume. Accanto ai materiali, restano tuttavia fondamentali per qualsiasi opera strutturale o infrastrutturale (e non potrebbe essere diversamente) la concezione strutturale, la gestione - con monitoraggio dei carichi effettivi - e la manutenzione.

Molti dei temi in precedenza menzionati sono affrontati nei sommari estesi delle venti tesi di dottorato discusse o approvate negli ultimi due anni accademici, in linea con la media di undici tesi all'anno nel periodo 2012-18. Và tuttavia osservato che la ben nota pandemia ha obbligato alcuni Dottorandi ad allungare i tempi per giungere alla conclusione del dottorato.

I 20 sommari estesi ricevuti dalla Commissione Giudicatrice giungono da 15 università italiane, con due collaborazioni con università straniere. Più di 1/3 delle tesi riguarda i materiali, mentre poco meno di 2/3 riguarda le applicazioni strutturali e le tecnologie innovative. In dettaglio:

- il 25% (5) riguarda i conglomerati cementizi innovativi (multifunzionali, con leganti non cementizi, con aggregato riciclato, ad alta lavorabilità, con fibre);
- il 35% (7) le costruzioni in c.a. e c.a.p. (riparazione e rafforzamento con strutture esterne, e con calcestruzzi contenenti fibre vegetali o basaltiche; strutture miste muratura-calcestruzzo; modellazione numerica con codici nonlineari; sperimentazione su conci per gallerie e su ancoraggi strutturali);
- il 25% (5) le condizioni estreme (per sisma, carichi ciclici, fuoco, corrosione chimica) ed il monitoraggio del danno;
- l'15% (3) le tecnologie innovative (la stampa tridimensionale di oggetti in conglomerato cementizio, negli aspetti sia del materiale, che delle tecnologie della fabbricazione additiva e della caratterizzazione meccanica dell'aderenza fra strati contigui).

I sommari sono stati esaminati da una Commissione Giudicatrice composta da cinque membri, di cui quattro accademici ed uno industriale. Secondo la lista di merito stilata dalla commissione (compito non facile!), otto sommari – 40% del totale - 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 ed ai Materiali Strutturali, come "ponte" fra Accademia ed Industria.

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Topic A

INNOVATIVE CEMENTITIOUS MATERIALS

COMMERCIAL AND RECYCLED CARBON-BASED FILLERS AND FIBERS FOR SMART MULTIFUNCTIONAL MORTARS

Alberto Belli

31st Cycle (17th new series) of PhD Course in Industrial Engineering: Materials Engineering

Università Politecnica delle Marche

Keywords: self-sensing concrete, piezoresistivity, graphene, carbon-based fillers, carbon fibers

Introduction

Concrete structures and buildings are a huge part of the built environment with reference to both recent and old constructions, and the major role played by concrete is not going to change in the foreseeable future. Consequently, the use of innovative cementitious composites in future constructions, as well as in the refurbishment of building heritage is something designers and architects have to become familiar with. In fact, despite its ancient origin, concrete is still evolving in accordance with materials innovations and technologies, in order to offer the best performance with the lowest environmental impact. In particular, multifunctional cement-based materials are a novelty in the field of materials science and nano-technologies [1]. Carbon-based materials, such as graphene and micro-fibers, are fostering a revolution in cement and concrete science [2], and high resistance and durability [3], as well as de-polluting and photocatalytic properties [4] are among the benefits to be expected. The exponential increase in concrete electrical conductivity, however, may be the most promising effect of these technologies [5]. Highly-conductive concretes, and their self-sensing properties, may be extensively used in civil engineering and infrastructures (such as bridges and tunnels), in order to develop monitoring systems [6].

Furthermore, using industrial carbon-based products and waste in concrete – still little studied - may make carbon-related technologies more sustainable, cheaper and applicable on a larger scale [7], by reducing the high costs typical of the complex production processes of hi-tech carbon-based materials.

The present research project aims to develop multifunctional cement-based materials using carbon-based fillers and fibers obtained from recycled industrial by-products. Their performance is compared in this study with that of industrial nano-fillers, such as graphene and virgin carbon fibers. Composites are investigated and compared in terms of mechanical strength, durability, and absorption of pollutants, as well as photocatalytic and electromagnetic-shielding properties. The electrical properties of multiphase composites, such as cement-based mortars with conductive carbon-based materials, and their self-sensing properties are examined as well.

Materials and methods

Multifunctional mortars have been developed in this project to investigate the effect of carbon-based fillers and fibers coupled with different types of hydraulic binders (hydraulic lime NHL 5, CEM I and CEM II/B-L). Natural aggregates with increasing particle size have been adopted to study the effect of the fillers in actual materials, as well as Graphene Nanoplatelets (GNP) and Activated Carbon Powder (ACP) among the commercial fillers. Gasification Char (GCH), obtained from the gasification of woodchips, and Used Foundry Sand (UFS) coming from waste steel-casting molds, have been also considered to obtain recycled carbon-based fillers. In the case of fibers, comparisons have been made between 6 mm-Virgin Carbon Fibers (VCFs) and Recycled Carbon Fibers (RCFs), resulting from the cutting of carbon panels.

The mechanical performance of multifunctional mortars was studied in terms of compressive and tensile strength, the latter in bending and in direct tension. Durability and de-polluting properties were investigated via capillary water-absorption and drying-shrinkage tests in the former case, and by performing tests on the adsorption of toxic agents and on photocatalytic efficiency in the latter case. The electrical resistivity was measured both under direct and alternate current, to understand the multiphase nature of the materials [13]. Measuring the Fractional Change in Resistivity (FCR), that is the variation in resistivity of the specimens under a given stress $\rho_{(t)}$ compared to the static value ρ_0, allowed to measure the piezoresistivity. The strain under stress $\Delta\sigma$ was measured as well, by using a strain gauge, in order to evaluate the stress sensitivity [8]:

$$FCR = \frac{\rho_{(t)} - \rho_0}{\rho_0} \qquad Sensitivity = \frac{FCR}{\Delta\sigma}$$

Results and discussion

The fresh composites with recycled fillers exhibit an appropriate workability, with an increase in the mechanical performance of 9 and 25% for the compressive and flexural strength, respectively. Microscopic analyses show that filler particles act as nucleation points for cement hydration [9], while the high hydrophobicity of graphene involves mixing problems and bleeding phenomena, with a high volume of voids and a sizeable segregation in the hardened material.

The addition of carbon fibers leads to an increase in both the flexural and tensile strength (up to 102% and 97% respectively). The best performance is obtained with recycled carbon-based fillers - RCFs, which increase the shear resistance at the microstructural level, thanks to the greater irregularity of the surfaces [10]. Fillers and fibers foster a microstructural refinement with a reduction in porosity and water absorption by up to 27%. Furthermore, the addition of recycled carbon-based fillers leads to a sizeable reduction in the drying shrinkage strain (up to 38%). The mixes containing foundry sand show a de-polluting behavior comparable to that of the mixes containing activated carbon, with a decrease close to 50% in the toxic-agent content, but none of the additions exhibits significant de-polluting capacity by photocatalysis.

All types of additions decrease the electrical resistivity of the composites, thanks to their conductivity and to their effect on the microstructure. Furthermore, when the amount of fillers and fibers exceeds a certain threshold (e.g. 0.15% by binder mass, for carbon fibers), the contact among the fibers and the *tunneling effect* increase exponentially the conductivity of the composites [11] and decrease the resistivity by several orders of magnitude. For instance, the addition of 0.8% of RCFs by binder mass decreases the resistivity of plain mortar from 7265 Ω·cm to 20 Ω·cm.

Under cyclic stresses, piezoresistivity tests have shown that the conductive composites developed in this research project have a sizeable electrical sensitivity and a variety of self-sensing behaviors (Figures 1,2). This research project emphasizes the potential of recycled carbon-based additions for the production of mortars and concretes with higher mechanical and durability performance, and better properties in terms of pollutants adsorption.

Materials with different levels of electrical conductivity and different stress-sensitivity have been developed, to be used in a variety of applications (self-sensors or entire structural members). Together with other monitoring methods, these technologies will be validated and implemented in large and real-scale systems, within projects funded by the European Commission [12].

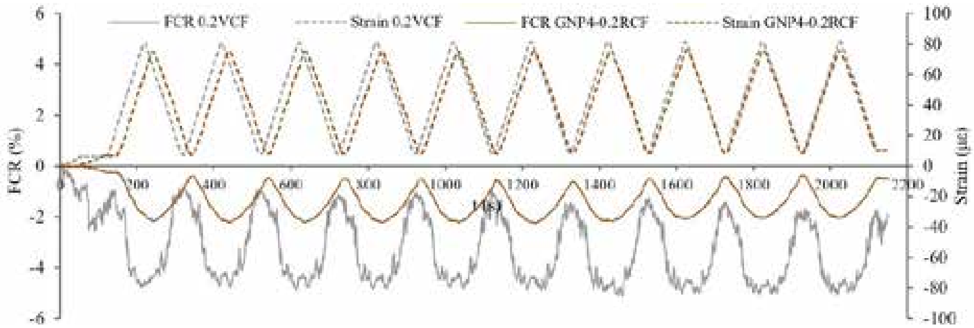

Figure 1. Piezoresistivity test based on the Fractional Change in Resistivity - FCR and strain vs. time: 0.2% of Virgin Carbon Fibers – VCFs, and Graphene NanoPlatenets – GNPs + 0.2% of recycled Carbon Fibers - RCFs.

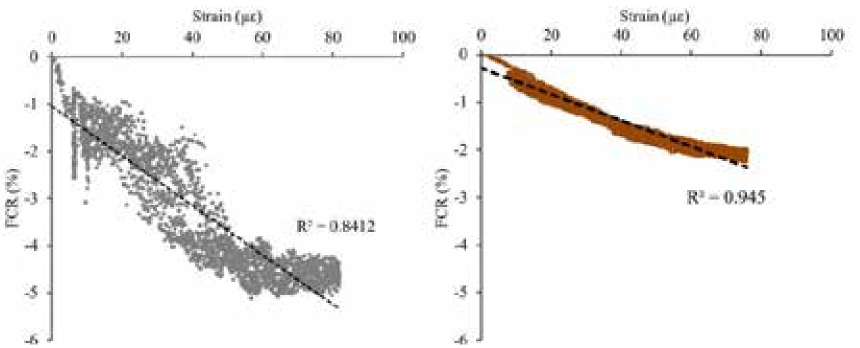

Figure 2. FCR vs. strain for 10 load cycles: 0.2% VCF (left) and GNP+0.2%RCF (right).

Final remarks and outlook

This research project emphasizes the potential of recycled carbon-based additions in the production of mortars and concretes with higher mechanical and durability properties, and a better adsorption capability face to pollutants.

Materials with different levels of electrical conductivity and different stress sensitivity have been developed, to be used in a variety of applications (self-sensors and entire structural members). Together with other monitoring methods, these technologies will be validated and implemented in large and real-scale systems, within projects funded by the European Commission [12].

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Original title of the thesis: *Comparison between Commercial and Recycled Carbon-Based Fillers and Fibers for the Development of Smart and Sustainable Multifunctional Mortars*.

Supervisor of the thesis: *Professor Francesca Tittarelli*.

MIX DESIGN AND PERFORMANCE ASSESSMENT OF SELF-COMPACTING CEMENTITIOUS MATERIALS FOR PAVEMENT FOUNDATIONS IN ROAD TUNNELS

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Keywords: construction sustainability, road tunnels, pavement foundations, self-compacting cementitious mixes, mix design (of cementitious materials)

Introduction

The road networks play a major role in the economic development and social integration, and road tunnels are an integral part of such networks. This research project is aimed at the development of self-compacting cementitious or cement-bound mixes (hereafter indicated as SC-CBMs) specifically designed for the construction of pavement foundations in road tunnels. Pavement foundations in road tunnels are different from conventional pavement foundations for several reasons. In particular, the presence of buried utility lines under the foundation creates inconveniences during the process of laying and compacting conventional cement- stabilized materials. Among the utility lines, high-voltage cables have to be backfilled with materials exhibiting a high thermal conductivity to improve heat dissipation and to guarantee an effective power transfer. Such specific requirements prevent the use of conventional unbound granular layers and cement-stabilized layers in the foundation of road tunnels. Conventional foundation layers also require a large volume of natural aggregates, which is a non-renewable resource in nature. Considering these factors, self-compacting cement-bound mixes containing sizeable amounts of recycled materials are developed in this research project for the construction of pavement foundations in road tunnels.

Experimental program

The experimental program was organised in three parts as described below. In the first part, an experimental investigation focused on the mix design of self-compacting cement-bound mixes to be employed in paving applications was carried out. A significant quantity of secondary raw materials such as reclaimed asphalt pavement (RAP) and mineral sludge were included along with natural aggregates in the formulation of the SC-CBMs. The recipes were defined by optimizing the packing of the aggregate skeleton and by checking the flowability characteristics of cement pastes and composite mixes. The long-term stiffness and strength properties were evaluated through triaxial and shear tests. Based on the results and their interpretation, a mix design procedure was defined.

In the second part of the thesis, the thermal properties of the previous mixes were investigated, with specific reference to the suitability of these mixes in situations that require the backfilling of buried high-voltage transmission cables. The use of SC-CBMs with superior thermal conductivity in the thermal backfills were found to increase the electrical capacity of the cables.

In the third part of the thesis, the performance characteristics of the SC-CBMs produced in a concrete batch plant were studied via laboratory and in-field tests. The properties under investigation included: flowability, compressive strength, resiliency and bearing capacity. The mixes prepared with a cement dosage of up to 100 kg/m^3 were found to possess the required properties of flowability, strength and stiffness. On the contrary, the mixes with higher cement dosages (150 kg/m^3 and 200 kg/m^3) failed to meet the performance-related requirements because of their high long-term strength, which makes the excavation process difficult. The results gave also information about the effects of the different components on the properties of the mixes and led to the definition of acceptance criteria for the quality control during the construction works. Furthermore, a case study of pavement design in a road tunnel was conducted, where relevant data about the temperature and traffic were available. In particular, a full-scale test section was constructed using self-compacting cement-bound mixes in the subgrade and in the foundation, overlaid by two asphalt layers. The subsequent investigation included measurements obtained with a falling-weight deflectometer (FWD) and laboratory tests, which were carried out for the assessment of the volumetric and mechanical properties of the mixes. Different pavement cross sections were analyzed as well, using these materials properties.

Results

The results of this research project are mainly about two issues: (a) the advancement of the existing knowledge in the domain of self-compacting cement-bound mixes with a new mix design methodology, and (b) the development of a new material suitable for the construction of pavement foundations in road tunnels and thermal backfills. The main results are:

1. Development of a mix-design procedure for self-compacting cement-bound mixes containing a significant quantity of recycled components.
2. Improvement in the thermal properties of self-compacting cement-bound mixes for thermal backfills and pavement foundations carrying buried electrical cables.
3. Development of performance-based acceptance criteria for the quality control of self-compacting cement-bound mixes; these criteria and the feasibility of pavement foundations with the proposed mixes were checked via large-scale field tests.
4. Construction and testing of a full-scale section of a pavement inclusive of the foundation, as a demonstration of the efficiency and reliability of self-compacting cement-bound mixes in pavement design and construction.

Industrial impact

The self-compacting cement-bound mixes developed in this research project are arising the interest of the contractors involved in the construction of road tunnels. In fact, the mix used in the large-scale test has been adopted in a ready-mix concrete plant and the concrete has been used in the construction of the pavement foundations in a major road tunnel in Italy (Figure 1).

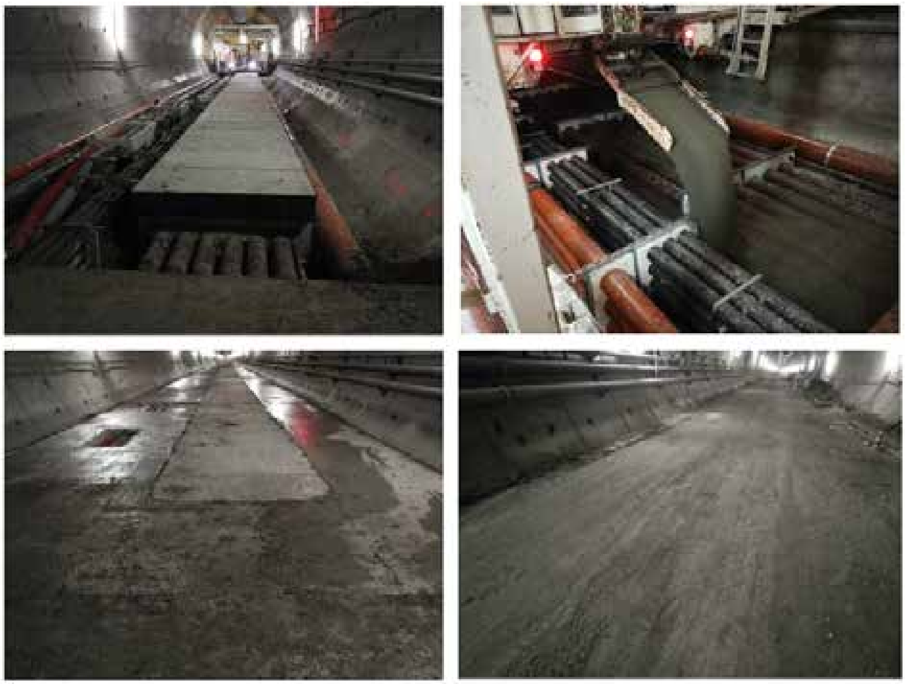

Figure 1. Actual construction of pavement foundations, using the mix designs proposed in this research project for self-compacting cement-bound mixes.

Concluding remarks

The results of this research project demonstrate the suitability of self-compacting cement-bound mixes for the use in pavement foundations of road tunnels. In the future, the proposed mix-design approach may be used for the development of self-compacting cement-bound mixes containing other recycled constituents, and the experimental investigation based on field tests (as done in this project) may be adopted for preparing performance-related provisions.

Self-compacting cement-bound mixes may be used in other applications like trench backfilling, embankment construction and flowable thermal backfills. In such a way, added value will be given to construction and demolition waste, with a sizeable contribution to sustainable construction.

Outlook

Fatigue and rutting properties of self-compacting cement-bound mixes are among the next issues to be dealt with.

Scientific publications from this research project

Choorackal E., Riviera P.P. and Santagata E. (2019). Mix design and mechanical characterization of self-compacting cement-bound mixtures for paving applications. *Construction and Building Materials*, V. 229, https://doi.org/10.1016/j.conbuildmat.2019.116894

Choorackal E., Riviera P.P., Dalmazzo D., Santagata E., Zichella L. and Marini P. (2019). Performance-related characterization of fluidized thermal backfills containing recycled components. *Waste and Biomass Valorization*, pp.1-12, https://doi.org/10.1007/s12649-019-00650-9

Santagata E., Choorackal E. and Riviera P.P. (2020). Self-compacting cement-bound pavement foundations for road tunnels: performance assessment in field trials. *Int. Journal of Pavement Engineering*, https://doi.org/10.1080/10298436.2020.1825709.

Riviera P.P., Bertagnoli G., Choorackal E. and Santagata E. 2019). Controlled low-strength materials for pavement foundations in road tunnels: feasibility study and recommendations. *Materials and Structures*, V. 52, No. 4, https://doi.org/10.1617/s11527-019-1367-4.

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Riviera P.P., Choorackal E. and Santagata E. (2019). Performance evaluation of innovative and sustainable pavement solutions for road tunnels. *Proc. 5th Int. Symposium on Asphalt Pavements & Environment (APE) – Int. Society for Asphalt Pavements – ISAP*, Padua (Italy), *Lecture Notes in Civil Engrg.*, V. 48, Springer, https://doi.org/10.1007/978-3-030-29779-4-40.

Original title of the thesis: *Mix Design and Performance Assessment of Self-Compacting Cement-Bound Mixtures for Pavement Foundations of Road Tunnels*.

Supervisors of the thesis: *Professor Ezio Santagata and Dr. Pier Paolo Riviera*.

THE BEST PATH TO SUSTAINABLE CONCRETE: LOW-CARBON BINDERS FOR SPECIAL APPLICATIONS

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Keywords: alternative binders, alkali-activated materials, calcium sulphoaluminate cement, sustainability index

Introduction

Concrete is by far the most used construction material in the world, with a production of more than 10 billion cubic meters. Due to this huge volume, concrete industry has a very strong environmental impact in terms of greenhouse gas emissions (about 2.8 Gt of carbon dioxide per year, approximately 7-9% of the total emitted worldwide), energy requirements (modern cement plants requires about 3.4 GJ/ton during clinker production, about 2-3% of the energy used worldwide) and consumption of natural materials (on average, 1.22 ton of limestone and 0.31 ton of clay are required to produce 1 ton of clinker) [1]. For these reasons, efforts have been lately made towards sustainable concrete, ranging from alternative constituents (binders, aggregates and water) to innovative admixtures and techniques able to improve concrete performance, prolong the service life and reduce the environmental impact.

The purpose of this work is to investigate two different binders as an alternative to Portland cement in the manufacture of sustainable mixes for special applications. In particular, alkali-activated slag-based binders (AAS) were studied to develop a pre-packed lightweight reinforced plaster for the thermal and seismic retrofitting of existing structures, while blends of calcium sulphoaluminate cement (CSA) and supplementary cementitious materials (SCM) were investigated in order to produce shrinkage-compensating concretes for jointless slabs on ground. Finally, a new sustainability index for cementitious materials – EASI – was developed taking into account the environmental impact, the performance and the durability of the mixes.

Alkali-activated slag-based binders

The performance of pre-packed alkali-activated slag-based mortars was evaluated in terms of rheological, physical, elastic-mechanical properties and environmental impact. The experimental results indicate that the key parameter that controls most of the properties (in both the fresh and hardened state) of alkali-activated compounds is the alkali content [2]. In fact, using AAS binders not only reduces the environmental impact by more than 80% with respect to Portland cement-based mixes (same strength class), but makes it possible to *tailor* both the mechanical strength and the workability of mortars through the dosage of the activator. In particular, high alkali contents bring in an increase in consistency (due to the interaction between sodium silicate and slag particles), promote slag hydration and improve the microstructure to the advantage of the compressive strength (Figure 1).

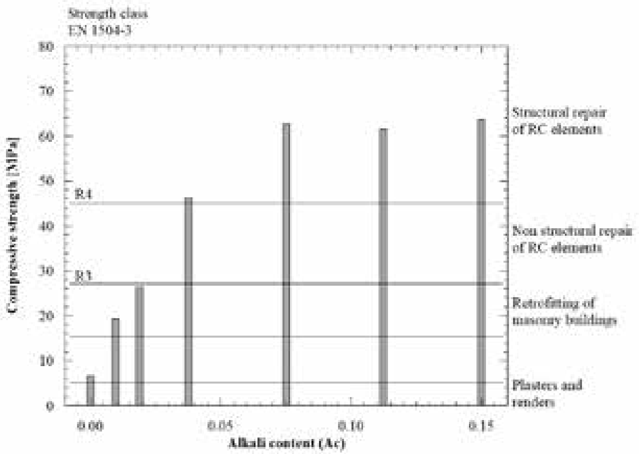

Figure 1. Compressive strength at 28 days of AAS mortars at different alkali contents, and possible uses as building materials

Moreover, a proper blend (CaO-based expansive additives, ethylene glycol-based shrinkage-reducing admixtures, plastic micro-fibres and viscosity-modifiers) was found to reduce the typical high shrinkage of AAS (up to 4000 μm/m after 150 days at 20°C and R.H. 60%) without affecting the microstructure and the mechanical properties [3].

A lightweight cement-free reinforced plaster for the thermal-insulating upgrading and seismic retrofitting of stone masonry buildings was developed, using alkali-activated slag-based binders. The use of expanded recycled-glass aggregates instead of natural sand, and the addition of an air-entraining agent reduce the density of mortars to 750 kg/m^3 and the thermal conductivity to 0.35 W/mK, and improve the energy performance of the masonry. At the same time, a proper mix design allows to obtain strength values suitable for structural reinforcement (compressive strength equal to 8 MPa at 28 days), elastic modulus close to 1.5 GPa and very low shrinkage, to the advantage of the adhesion to bricks and stones (up to 1.16 MPa). Finally, using an alchil-alcoxisilane-based coating was shown to reduce by about 80% the water absorption by the plaster. In this way, mortar on-site saturation can be avoided in raining periods [4].

Calcium sulphoaluminate cement-based blends

The use of sustainable SCMs, such as fly ash, ground granulated blast furnace slag and silica fume in the CSA-based mixes strongly reduces the environmental impact of concretes and mortars (CO_2 emissions and energy consumption are reduced by about 50-60% vs. traditional cementitious materials for the same strength class). A blend of

SCMs and CSA is an interesting opportunity to reuse solid industrial wastes and to obtain quick-setting expansive mixes with excellent mechanical properties. The results indicate that, in job-site applications, it is necessary to use a set-retarding admixture able to improve the workability retention without affecting the 28-day mechanical strength [5]. It was found that tartaric acid, whatever the nature of SCMs replacing Portland cement, acts as (a) a superplasticizer, (b) a corrosion inhibitor and (c) an effective means to extend the pot-life of mortars up to 2 hours, without side-effects on density, strength and expansive behaviour [6,7]. The low resistance to carbonation can also be improved by adding a hardening accelerator based on sodium and lithium carbonate, able to reduce the carbonation rate by about 60% thanks to the densification of the microstructure [8].

The influence of the water/binder ratio and of the curing conditions on the properties of CSA-SCMs blended binders was investigated to define possible correlation curves for the prediction of the mechanical properties of the concretes manufactured with environment-friendly CSA-based binders. Abram’s law and modified Eurocode models can still be used to evaluate the main elastic-mechanical parameters of CSA concretes cured in different conditions. Finally, the expansive behaviour of these mixes make them interesting in all the applications requiring shrinkage compensation [9].

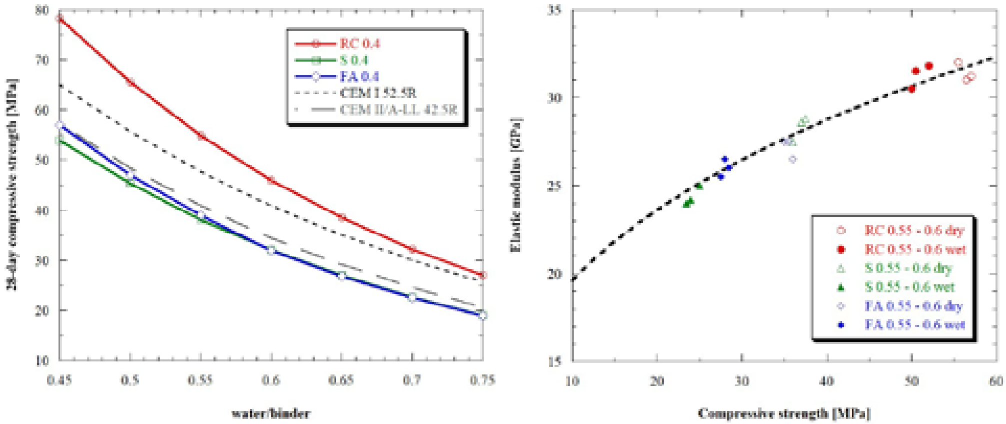

Figure 2. Compressive strength at 28 days vs. water/binder ratio (left) and elastic modulus vs. compressive strength (right). Binders: RC = CSA cement and Portland cement, S = CSA cement and ground-granulated blast-furnace slag, FA = CSA cement and fly ash. Tartaric acid dosage/ binder mass = 0.4 or 0.6; water/binder ratio (right only) = 0.55.

Sustainability index

A new sustainability index (Eq.1) was developed taking into account the environmental impact (EI), the performance (P) and the service life (SL) of the mixes. In particular, in the environmental impact section, the natural raw-materials consumption, the greenhouse-gas emission and the energy consumption have been considered [1]. Furthermore, depending on the applications and environmental conditions, design parameters and properties related to durability have been assigned to each mixture.

$$EASI = \frac{n \cdot \prod_1^j P \cdot \prod_1^k S_L}{\sum_1^n EI} \qquad (1)$$

Outlook

Improving the sustainability of concrete cannot be limited to decreasing the environmental production-related impact, because - should it be accompanied by a strength loss or by a shortening of the service life, no real improvement in sustainability would be achieved. For this reason, it is fundamental to promote in-depth studies on the performance and durability of binders other than Portland cement, in order to define their *real* sustainability, always bearing in mind that one of the main options to obtain a *green concrete* is to improve its durability or to enhance its performance without increasing the environmental impact.

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Original title of the thesis: *Alternative binders as milestone of 3R strategy for sustainable construction materials*.

Supervisor of the thesis and Tutor: *Professors Luigi Coppola and Tommaso Pastore*.

SHORT- AND LONG-TERM PERFORMANCE OF CONCRETE CONTAINING MACRO-SYNTHETIC FIBRES: AN EXPERIMENTAL AND NUMERICAL INVESTIGATION

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Keywords: fibre-reinforced concrete - FRC, macro-synthetic fibres, fibre pull-out, high-performance fibre-reinforced concrete – HPFRC, lattice discrete particle model – LDPM

Introduction

Fibre-reinforced concretes (FRCs) are composite materials characterized by a normal- or high-strength cementitious matrix, containing a discrete fibrous reinforcement. The principal aim of fibre addition is to overcome the weak aspects of concrete, mainly related to its limited tensile strength and little resistance to crack propagation [1].

The objective of this work is to investigate the mechanical performance of different types of macro-synthetic fibres often adopted nowadays as a reinforcement in normal-strength and high-strength concrete. In addition, a novel numerical approach is developed in order to describe the short- and long- term behaviour of this composite material. The focus is on the fundamental aspects of concrete reinforced with macro-synthetic fibres (MSFRC) as a structural material. Firstly, the constitutive relations at the small scale of the interface between the fibre and the matrix are formulated. Secondly, the behaviour in the cracked state is examined at the material scale. Thirdly, the in-time behaviour of FRC (still an open issue [2]) is investigated.

Experimental programme

The characterisation of fibre-to-concrete interface was performed by pulling-out polypropylene fibres (bonded length 20 and 25 mm) embedded into a number of mortars with two cement types (CEMI 42.5R and CEMI 52.5R), three cement/sand ratios (0.2, 0.3, 0.5) and four water/cement ratios (0.40, 0.45, 0.50, 0.60).

Three-point bending tests and uniaxial compressive tests were carried out to characterize the residual strength of three concrete classes (33 – 55 MPa) combined with four fibre dosages (2, 4, 6, 8 kg/m^3). The results of the pull-out and flexural tests were used to calibrate the local bond-slip and stress-crack opening laws, respectively. The flexural response was studied also in the case of high-performance FRCs containing polyvinylalcohol (PVA) fibres, whose mixes had recycled aggregates.

Tests were performed also on 55 MPa concrete reinforced with polypropylene fibres (8 kg/m^3) to investigate creep in different loading conditions, and shrinkage.

Numerical model

The numerical approach is based on the lattice discrete particle model [3], that is an extensively-validated mesoscale model, aimed at describing the interaction among aggregate particles, fibres and the cementitious matrix. The model is based on a number of constitutive laws whose numerous parameters were calibrated through the bending and creep tests, to describe the short- and long-term behaviour of fibre-reinforced concrete. The most innovative aspect of the model (previously calibrated and validated for concrete [4]), is the inclusion of fibre viscoelasticity, to predict the time-dependent deformations of FRC containing macro-synthetic fibres.

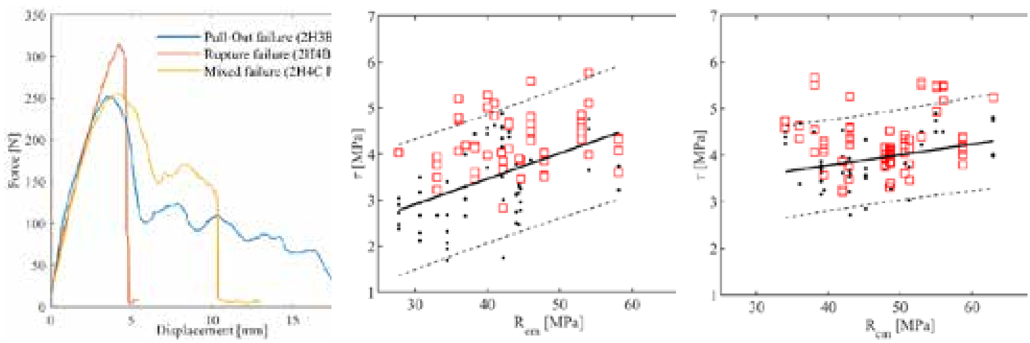
Experimental results

The fibres tend to break or to slip out of the matrix as shown by the pull-out tests (*Figure 1*a), where the peak force was controlled either by the tensile strength of the fibres (first failure mode) or by bond strength (second failure mode). In some cases, however, a mixed-mode failure occurred. In *Figure 1*b-c the correlations between the peak bond stress (= bond strength) and the compressive strength (for different concretes and two types of cement) show that the stronger the concrete, the smaller the correlation.

According to the European Standard EN 14651, the flexural capacity of the FRCs is expressed by the residual strength at certain values of the crack-mouth opening displacement (CMODs). Those values are correlated with the matrix strength and the number of the fibres (per unit surface of cracked area), but the dependence on the number of the fibres (*Figure 2*) is very pronounced.

The bond stress–fibre slip and stress–crack opening laws (not plotted in this long abstract) were derived from the test results and their calibration was performed by means of inverse analysis.

Regarding the long-term behaviour, *Figure 3* illustrates some results of shrinkage and creep tests on cylinders, prisms and fibres, while an example of force-displacement curve in 3-point bending is shown in *Figure 4*.



(a) (b) (c)

Figure 1. Pull-out tests: (a) force-displacement curves; and (b,c) linear regressions of the bond strength vs. the compressive strength for the specimens with CEMI 42.5R (b) and CEM I 52.5R (c).

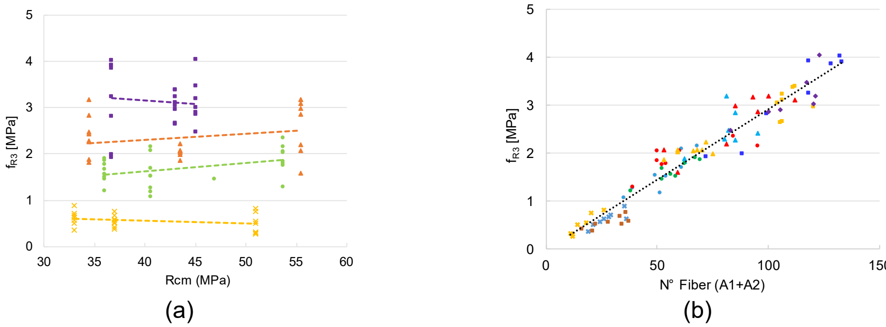


Figure 2. Three point bending tests: (a) f_{R3} vs. compressive strength; and (b) f_{R3} vs. number of fibres.

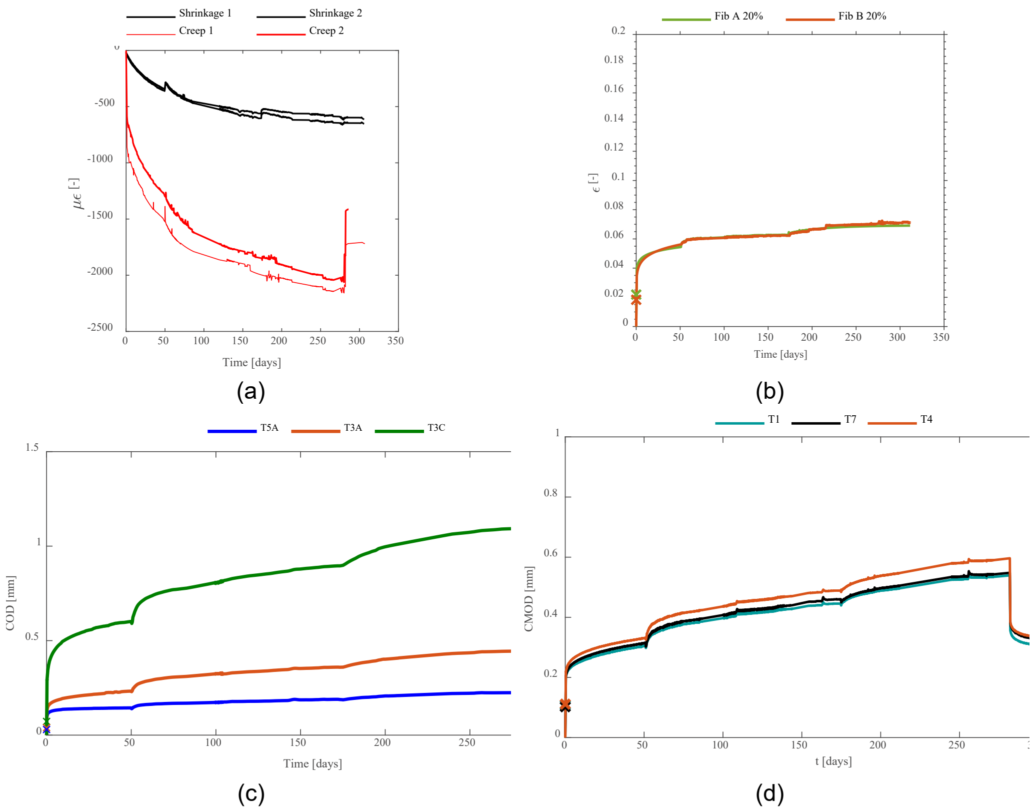
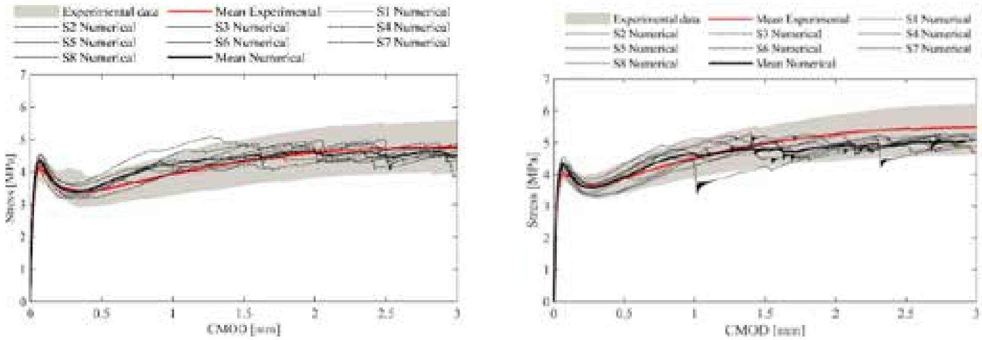


Figure 3. Creep and shrinkage tests on concrete cylinders (a); tensile tests on single fibres (b); creep tests in tension on MSFRC cylinders (c); and creep tests in bending on MSFRC prisms (d).

Numerical results

The Lattice Discrete Particle Model - LDPM was adopted to calibrate (*Figure 4a*) and validate (*Figure 4b*) the short-term behaviour of fibre-reinforced concrete on the same concrete reinforced respectively with 8 kg/m^3 and 10 kg/m^3 of fibers, while concrete and fibre viscous-elastic behaviour were modelled separately and then merged into the calibration of the tensile-creep tests.



(a) (b)

Figure 4. MSFRC flexural tests: (a) calibration – fibre dosage 8 kg/m^3, and (b) validation – fibre dosage 10 kg/m^3.

Concluding remarks and outlook

The roles of the parameters influencing the behaviour of macro-synthetic fibre-reinforced concrete (MSFRC) – concerning mainly fibre amount and creep properties, as well as fibre-to-concrete interface – have been clarified through appropriate tests and the implementation of the ensuing constitutive laws into a powerful code based on the Lattice Discrete Particle Model makes it possible to describe the short and long term behaviour of MSFRC, through a reliable modelling of the heterogeneity of concrete aggregates and fibre distribution.

The role of fibre orientation and creep of single fibres at different temperatures, as well as the numerical modelling of the interaction among the different resisting mechanisms are among the issues requiring further investigation.

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Original title of the thesis: *Experimental and Numerical Investigation on Short- and Long-Term Performance of Macro-Synthetic Fibre-Reinforced Concrete Materials*

Supervisors: *Professors Claudio Mazzotti and Nicola Buratti*

Cosupervisors: *Professors Roman Van-Wendner and Jan Vorel*

SHORT AND LONG-TERM BEHAVIOUR OF STRUCTURAL AND NON-STRUCTURAL MEMBERS MADE WITH CALCIUM SULFOALUMINATE CEMENT

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Keywords: Environmental impact, calcium sulfoaluminate mortars and concretes, blended cements, physical and mechanical properties (of blended cementitious composites), creep behavior, RC beams, structural long-term behaviour (of RC).

Introduction

Ordinary Portland cement (OPC) is still the most widely used binder in concrete construction. The necessity to reduce the global emission of carbon dioxide, however, has been the driving force behind the development of new cementitious binders; in this context, a marked increase in the use of calcium sulfoaluminate (CSA) cements is in progress. The lower temperature necessary for the production of CSA-based clinker and the relative lower emission of carbon - dioxide compared to OPC (in the range -25%-35%) – makes CSA cements *green*. CSA cements can be also mixed with OPC generating OPC/CSA blended systems, in order to combine the mechanical and green properties of the two binders. Although CSA cements have satisfactory properties, there is still little information on their long-term behaviour and durability, especially in the case of reinforced-concrete members.

The scope of this research project is to investigate the performance of CSA cements to be used in structural and non-structural applications. Several mortar and concrete mixes are investigated in terms of properties in the fresh and hardened state, chemical composition and volumetric properties, for various OPC/CSA cement ratios. The long-term flexural behaviour of real-scale RC beams is investigated as well, with the focus on the influence that the environment and the concrete type have on the flexural response. The results are aimed at shedding light on how the properties of CSA cements alone or in combination with Portland cement may affect the performance of structural members, all the more because of the limited literature on this topic.

Experimental programme

Six different mortar mixes were made with water-cement ratio (w/c) equal to 0.5 and different values of the OPC/CSA binder ratio (OPC/CSA = 100/0, 70/30, 60/40, 50/50, 0/100; OPC/CSA+gypsum = 60/40). Note that 100/0 and 0/100 are also indicated with “OPC” and “100CSA”. The long-term properties in the fresh and hardened state were investigated in terms of: workability, air content, compressive strength, flexural strength, splitting tensile strength, elastic modulus, volumetric properties (drying and autogenous shrinkage, plastic shrinkage, creep), internal RH, RH profiles and chemical composition (thermogravimetric analysis - TGA and X-ray diffraction analysis - XRD).

Moreover, seven concrete mixes were made with different values of the OPC/CSA binder ratio (OPC/CSA = C100/0 two slightly-different mixes - indicated with “COPC” and “COCP+”-, C70/30, C60/40, C50/50, C0/100; OPC/CSA+gypsum C60/40). Note that “C” prior to the OPC/CSA ratio stands for “concrete”. C100/0 and C0/100 are also indicated with “COPC” and “C100CSA”.

The long-term mechanical properties were evaluated in the fresh and hardened state as in the case of the mortars, and so for drying shrinkage and mass changes.

The flexural behavior of RC beams made with the above-mentioned concrete mixes was investigated as well, both in the short and long term. To this end, twenty-five real-scale beams were designed and cast (no beams with the mix C60/40). Five beams, one for each concrete mix (OPC/CSA = C100/0 two mixes, C70/30, C50/50, C0/100), were tested in 4-point bending, 56 days after casting, with the focus on moment-curvature curves, ultimate capacities, strains (in both concrete and bars) and crack patterns.

Ten beams (two for each concrete mix) were exposed to the Mediterranean environment under sustained loads applied by means of an experimental setup taken from the literature [3, 4].

The remaining (ten beams, two for each concrete mix) were exposed to the Mediterranean environment without loads, for future tests (Figure 1).

In the beams exposed to the environment and in service conditions the mid-span deflection and the crack pattern (crack width, number, vertical extension) were continuously monitored. The width of the cracks was compared with that predicted by the analytical expression suggested in Model Code 2010 [5] to check whether this expression be applicable also to structural members made of CSA cement.

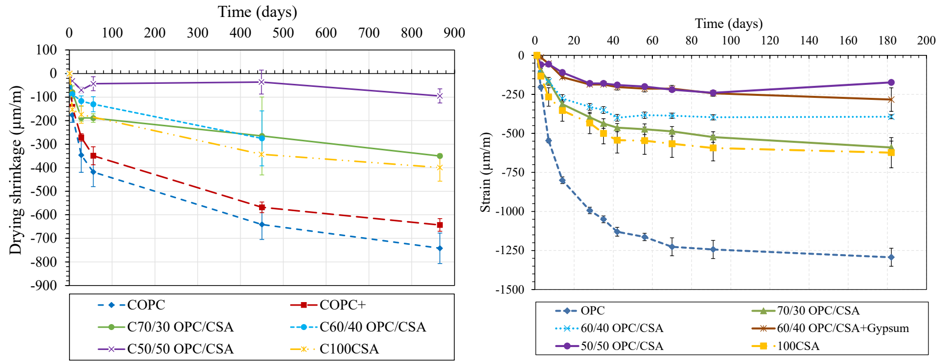
(a) (b)

Figure 1. (a) Four-point bending setup; and (b) beams exposed to the open air [6].

Test results

- Increasing the amount of CSA cement caused an increase in the mechanical properties of both mortars and concretes one day after casting. In the same situation, the elastic modulus had similar values in all the concretes, in spite of the higher compressive strength of OPC/CSA concretes.

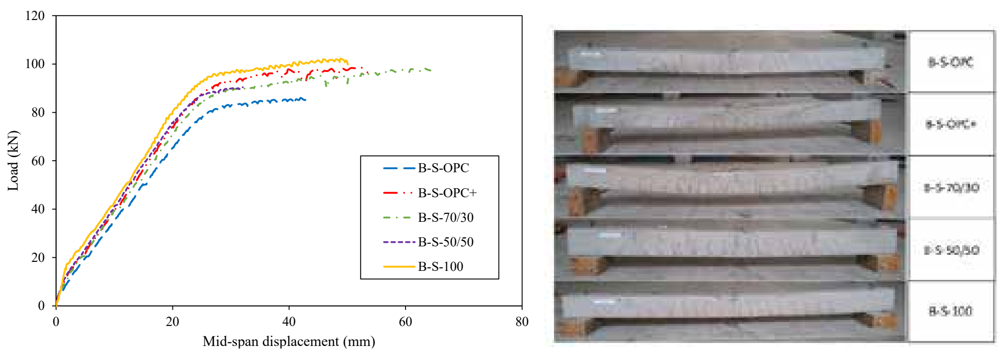
- High creep deformations in drying conditions were measured in the mortar and concrete with OPC/CSA = 70/30. Moreover, decreasing the OPC/CSA brought in a reduction in mass-change percentage and drying shrinkage (Figure 2).



a) b)

Figure 2. Drying shrinkage: (a) concrete mixes [6], and (b) mortar mixes.

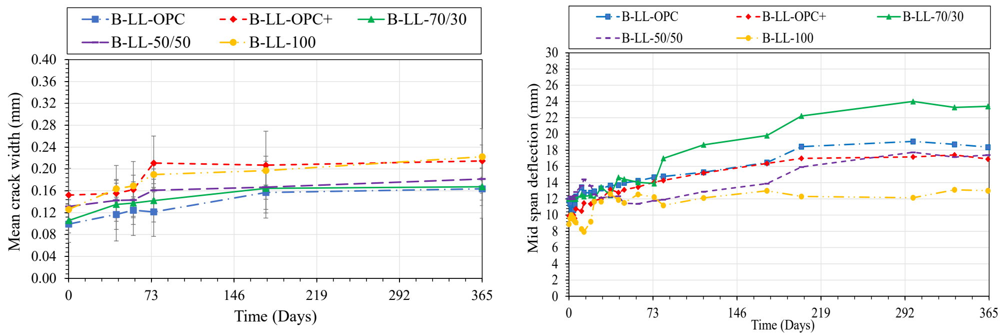
- In general, increasing the amount of CSA makes the flexural behaviour stronger. The higher ductility observed in the case OPC/CSA = 70/30 (Beam B-S-70/30) was probably caused by concrete relaxation. Furthermore, a short-term improvement in the crack pattern (with thinner and more regular cracks) was observed when pure CSA cement is used (B-S-100, Fig. 3).



a) b)

Figure 3. Short-term bending tests: (a) load-midspan displacement curves, and (b) at failure.

- The analytical model suggested in Model Code 2010 for the calculation of the crack width seems to greatly overestimate the experimental values, both in the short and long term, in the case of the beam made using C100CSA concrete.
- Monitoring the beams exposed to the environment in service conditions allows to observe a long-term positive contribute of CSA cement in terms of crack pattern for the beams where 50% of OPC is replaced with as much CSA binder (B-LL-50/50 beam, Figure 4). On the other hand, the beam B-LL-70/30 (Figure 4) exhibited a higher deformability.



a) b)

Figure 4. (a) Average crack width vs. time, and (b) midspan deflection vs. time [6].

Concluding remarks

Calcium sulfoaluminate - CSA cement in combination with ordinary Portland cement - OPC improves concrete mechanical properties (especially the compressive strength) and reduces shrinkage in drying conditions. In general, the higher the CSA content, the lower shrinkage and creep strains. Furthermore, with an amount of CSA cement equal to or higher than 50% of the total cement content, long-term improvements occur concerning crack patterns and mid-span deflections.

Outlook

The few data available in the technical-scientific literature on both short-term and long-term performance of CSA mortars and concretes require further studies to be carried out. For such a reason, five extra beams will be tested after a 6-year exposure time.

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Supervisors of the thesis: *Professors Maria Antonietta Aiello and Marianovella Leone.*

Topic B

R/C AND P/C STRUCTURES

B0 - Strengthening and Retrofitting

GRID-BASED EXOSKELETONS AS A SUSTAINABLE TOOL TO STRENGTHEN EXISTING RC BUILDINGS IN A LIFE-CYCLE PERSPECTIVE

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Keywords: diagonal-grid (diagrid) exoskeletons, outer structural retrofit, life-cycle technologies - LCTs, RC buildings, design spectra, structural renovation/strengthening

Introduction

The deep renovation of the existing building heritage is now acknowledged as a priority to foster safety and sustainability across Europe. Despite the multiple needs of the existing buildings, their renovation rate is low (1.5% [1]), and the retrofit solutions are still conceived in an uncoordinated manner by addressing very sectorial issues and targeting one single topic at a time (energy efficiency or structural rehabilitation).

A new and integrated approach to building renovation is therefore required, and new techniques and solutions must be conceived to overcome the barriers to renovation, pursuing sustainability, safety, and resilience at the same time [2].

Within such a framework, the original contribution of this research project lies in the proposal of *diagrid exoskeletons* as a possible integrated technique to be adopted as a fresh start in renovation; in this context, additional design targets and operative choices based on the principles of Life Cycle Thinking (LCT) have been proposed, and simplified static schemes for the retrofitting diagrids and design spectra have been developed as a preliminary step in the design of retrofit exoskeletons.

Diagrids were first introduced as efficient bearing structures for tall buildings, since they consist of inclined structural grids withstanding both vertical and horizontal loads (Figure 1).

The reasons for choosing diagrids are the following: 1) diagrids are suitable in the integrated renovation projects (like those concerning many typical post-WWII RC structures built between the 60s and the 80s generally characterized by anonymous architectural features); 2) diagrids can be applied from the outside in so overcoming one of the main barriers affecting the current renovation practice (the need to relocate the occupants or the extended downtime required during the construction works); 3) diagrids may be assembled in different steps over an extended time by adopting incremental rehabilitation strategies thereby increasing the economic sustainability of the interventions; and 4) diagrids may be designed in full compliance with the principles of Life Cycle Thinking [2].

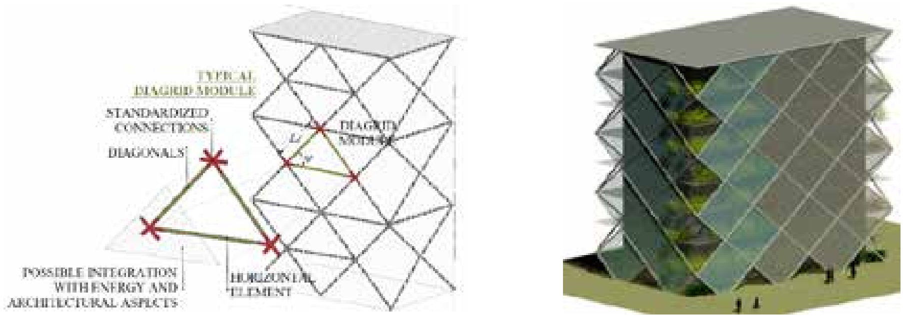


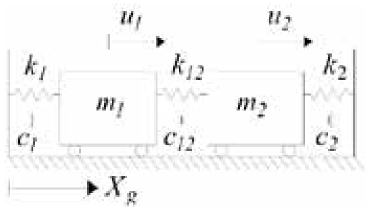
Figure 1. (a) Main components of a diagrid system; and (b) example of a retrofitting diagrid; in this case, the horizontal elements are provided with stiff external new diaphragms.

In this research project, (1) the simplified static schemes used for diagrids as bearing structures of new tall buildings [3, 4, 5] are revisited and adapted to seismic strengthening; (2) based on the preliminary works conducted by Ciampi [6] and Feroldi [7], sensitivity analyses are carried out on a simplified 2DOF system to investigate the optimal design parameters; (3) additional design targets and operative choices based on LCT principles are introduced; and (4) two design procedures for retrofitting diagrid exoskeletons are proposed and validated through nonlinear analyses based on a 3D finite element model (FEM).

Analytical and numerical structural models

Two straightforward procedures for the design of diagrids as retrofit tools are proposed; both take care of architectural aspects and minimum-stiffness requirements to meet target displacements and allowable stresses compatible with diagrid members.

The two procedures differ in the method used to define the minimum elastic stiffness required to meet the target displacements.



$$m_1(\ddot{X}_g + \ddot{u}_1) + k_1 u_1 + c_1 \dot{u}_1 = k_{12}(u_2 - u_1) + c_{12}(\dot{u}_2 - \dot{u}_1)$$
$$m_2(\ddot{X}_g + \ddot{u}_2) + k_2 u_2 + c_2 \dot{u}_2 = -k_{12}(u_2 - u_1) - c_{12}(\dot{u}_2 - \dot{u}_1)$$

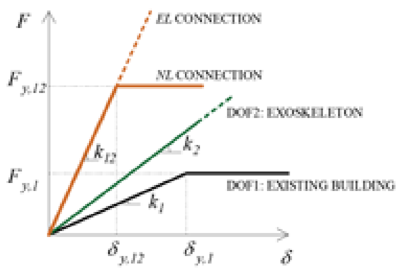


Figure 2. (a) 2DOF model; and (b) response curves of the retrofitted structure with 2DOF.

The first (analytical) method assumes that the bearing system can be modeled as a cantilever deep beam inclusive of the discrete nature of the diagrid [3, 4, 5], subjected to specific loads. The required stiffness of the diagrid and the cross-section of the members can thus be derived by addressing the Timoshenko theory.

The second (numerical) method is based on the results of sensitivity analyses carried on a simplified 2DOF system in which the system DOF_1 represents the existing building and the system DOF_2 the diagrid exoskeleton (Figure 2). The two systems are connected via a link that has been considered both elastic (EL) and nonlinear (NL).

Main results

To design the diagrids according to the LCT principles, a change of perspective has been introduced, and new design targets and operative choices have been proposed.

Two methods for the design of diagrids as structural retrofitting systems for RC buildings have been proposed and applied. The theoretical results have been compared with the results obtained with nonlinear time-history analyses carried out via a 3D FEM model, and the two proposed design procedures appear to be both very effective.

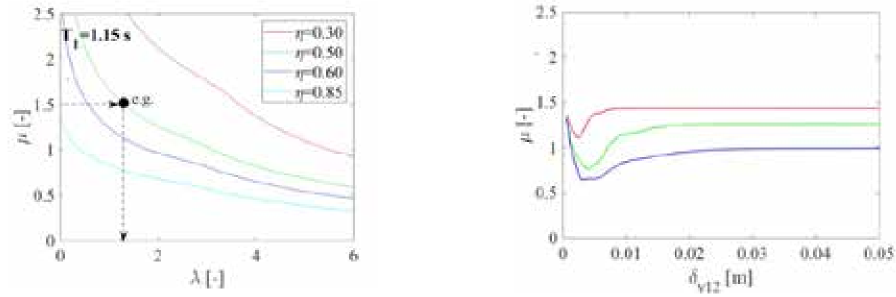


Figure 3. (a) Design-spectra example; and (b) ductility demand (μ) as a function of the yielding displacement of the non-linear connections ($\delta_{y,12}$).

Furthermore, the results yielded by the parametric analyses carried out on the simplified 2DOFs can be extended to any retrofit solution *from outside*.

As a first step, compact graphical design tools (*design spectra*) – linking the idealized inelastic responses of the retrofitted existing building to the elastic retrofit features - are derived (Figure 3a); in this way, the responses of different retrofit solutions may be directly compared, making it possible to optimize the parameters for the retrofit system itself. From the design spectra the stiffness of the retrofit (expressed through the normalized stiffness λ) can be obtained as a function of a number of target displacements (expressed through the ductility μ required to the system DOF_1 in case of a seismic event) and of the features of the existing building (e.g. elastic period T_1 and the strength parameter $\eta = \frac{F_{y,1}}{[m_1 \cdot S_a(T_1)]}$ defined for the system DOF_1 in the AS-IS condition). Note that the results are expressed in terms of η to avoid the dependency on the seismic site.

As a second step, the influence of the connections between the existing building and the exoskeleton is addressed. Note that (1) considering the sole stiffness of the exoskeleton (without considering the connection) leads to a substantial under-estimation of the required stiffness; and (2) introducing a nonlinear connection with reference to a set of displacements at the yielding of the connection itself ($\delta_{y,12}$) and plotting μ as a function of $\delta_{y,12}$, make it possible to identify a point of minimum, which indicates the optimal yielding value of the connection (Figure 3b).

Concluding remarks and outlook

An application of a new multi-criteria performance-based design approach is described; new targets are proposed to meet LCT principles and a simplified method for designing diagrid exoskeletons is proposed and validated. Design spectra for the design of diagrid are derived; the use of these spectra can be extended to all the retrofit solutions implemented from outside.

Research on the organic renovation *from outside* of existing RC buildings like those built after WWII RC is still going on and interest in this field is growing in Europe. Different frameworks and procedures are still being developed as a support for a new and integrated design approach, where diagrids may play a major role.

As for the design spectra, studies are still under way to further develop these tools and to make them accessible for various applications either research-oriented (like in cost-benefit and energy analyses) or engineering-oriented (like in the preliminary evaluation of the consequences of the adoption of different retrofitting strategies).

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Original title of the thesis: *Holistic Sustainable Renovation of Post-World War II Reinforced-Concrete Building under a Life-Cycle Perspective by means of Diagrid Exoskeletons*

Supervisor of the thesis: *Professor Alessandra Marini*

FLAX-BASED TEXTILE-REINFORCED CEMENTITIOUS MORTARS FOR MASONRY STRENGTHENING: FROM MATERIAL IDENTIFICATION TO STRUCTURAL BEHAVIOUR

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Keywords: textile-reinforced mortars – TSMs, fibre-reinforced cementitious matrices – FRCMs, vegetable fibres, flax, masonry, shear capacity (of masonry walls), sustainable composites

Introduction

Seismic hazard and many vulnerable constructions expose the Mediterranean basin to a high seismic risk, which requires urgent solutions to reduce expected losses in terms of human lives and damage to the built environment [1].

The increasing awareness towards the preservation of our environment is a crucial aspect of our society at different levels. In the construction field, a new class of systems is entering the scene, based on *green* building materials, that meet both mechanical and ecological requirements [2].

Inorganic matrix composites (Textile-Reinforced Mortars, TRMs), consisting of high strength fibres embedded in cementitious or lime mortars, are part of an innovative and efficient strengthening technique aimed at improving the capacity of structural members, with specific reference to masonry buildings [3].

In spite of their great potential, TRM composites containing plant-fibre textiles are still characterised by several issues, that prevent their diffusion on the market [4]. It is, therefore, necessary to intensify the research efforts on TRM composites to have a deeper knowledge of their mechanical behaviour, and to improve their efficiency as required by structural applications.

Within this context, in the present study a comprehensive investigation is performed on an innovative sustainable plant-based TRM system, in which flax fibres are used. The investigation is about flax-based TRM mechanical properties, as well as TRM efficiency and limitations in strengthening structural masonry members. In addition, the proposed strengthening system is shown to be suitable for further improvements.

Experimental programme

The flax-based TRM composite systems in question include a hydraulic lime-mortar matrix and a reinforcing flax-based textile (Figure 1a). In order to fully characterise the mechanical behaviour of the systems, an extended experimental programme, at different scales, has been devised, inclusive of: investigations on the reinforcing textile and on TRM composite systems, tests on masonry walls externally strengthened via flax-based TRM, and innovative techniques to improve the mechanical behaviour of the strengthening systems. All the steps agree with existing standards and guidelines, under the umbrella of *sustainability*.

The experimental programme is subdivided into three main parts:

- Mechanical characterisation of the composites - Tests were performed to evaluate: the tensile strength of the flax-based textile; the tensile strength of flax-based TRM (RILEM [5]); the bond between flax-based TRM and masonry units (RILEM [6]); and the durability of flax-based TRM (AC 434 [7]).
- Tests at the structural scale - Diagonal-compression tests were carried out on un-strengthened and externally-strengthened (via flax-based TRM) clay-brick masonry panels (ASTM E519-2 [8]).
- Improvements of the proposed technique - Tensile tests were carried out after the impregnation of the textile, on flax-based TRMs, devoid of - or containing - short pineapple fibres (*curauá fibres*; hybrid flax-based TRMs).

Test results

The tensile tests on flax-based TRM composites show that the response in tension has a trilinear behaviour characterised by a very steep softening (Figure 2, curve1), contrary to the typical behaviour of conventional high-strength fibre-based TRMs. An explanation for such behaviour may come from the low initial stiffness of plant fibres when subjected to tensile loading. The proposed composites, however, are very effective, as the fibre exploitation-ratio is close to 70 %.

As for the durability of flax-based TRM composites exposed to the environment according to a conventional ageing protocol, the tests demonstrate that the proposed composites comply with the usual acceptance criteria.

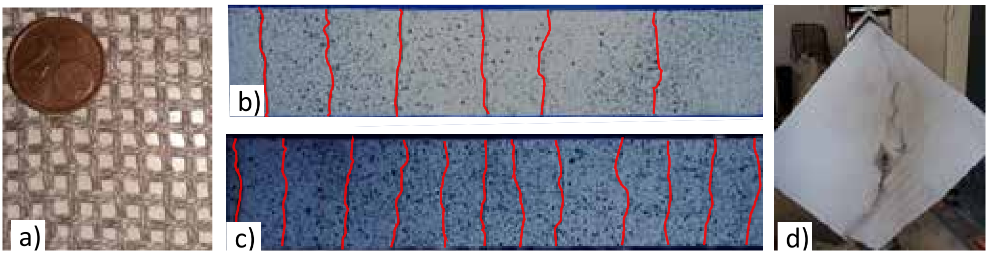

Figure 1. (a) Flax-based textile; (b) flax-based TRM; (c) hybrid flax-based TRM at the onset of failure in tension; and (d) failure mode of a masonry-wall specimen externally strengthened by means of flax-based TRM.

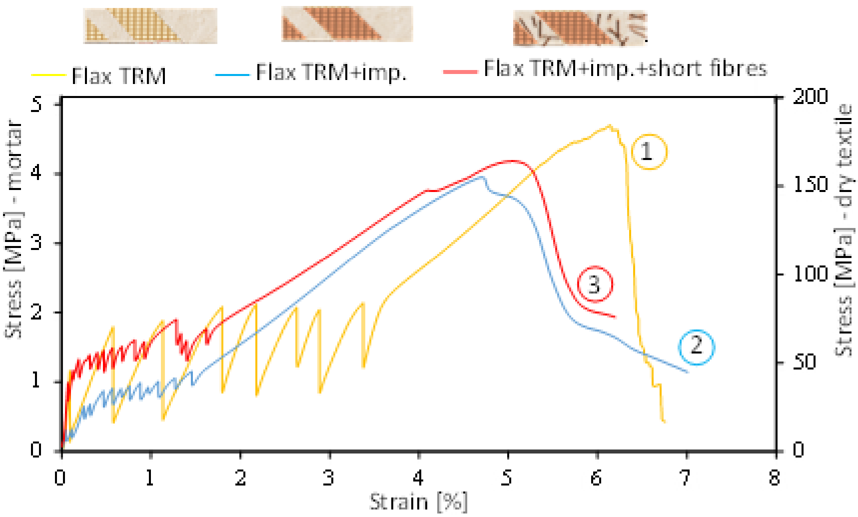

Figure 2. Stress-strain curves in tension of flax-based TRM (1), impregnated flax-based TRM (2), and hybrid impregnated flax-based TRM containing short curauá fibres (3).

At the global scale, the application of the flax-based TRM system significantly affects the mechanical response of the masonry panels tested in diagonal compression, by increasing their shear capacity and providing a ductile behaviour, completely absent in unreinforced panels. Furthermore, in the post-failure phase the panels exhibit a sort of integrity (Figure 1d). The tests show also a significant strength loss soon after the peak load and the formation of the diagonal crack.

As for the possible improvements of the proposed technique, impregnating the flax-based textile leads to a sizeable improvement in the mechanical response of the system as shown by Curve 2 in Figure 2, compared with Curve 1. It is true that impregnation slightly decreases the resistance (peak load), but the softening is significantly gentler, thanks to the formation of thinner and more dispersed cracks. Moreover, impregnation considerably reduces the deformability of the system with a value of the transition strain between the second and third stages reduced by about 50 % with respect to the reference mortar.

Coupling textile impregnation and the introduction of short curauá fibres into the TRM system further improves the behaviour of the mortar, by increasing slightly the resistance and markedly the regularity of the softening stage (Figure 2, curve3). Even more than after impregnation, adding short curauá fibres (hybrid flax-based TRM system) makes cracks thinner and more densely-distributed (Figure 1b and c), which is the reason of the gentler softening.

Concluding remarks

The large number of the experimental results presented in this study is meant to favour the use of plant textiles as a reinforcement in textile-reinforced structural mortars, and at the optimization of the various components, in order to increase the appealing of such sustainable materials. The main findings can be summarised as follows:

- Flax-based textile-reinforced mortars exhibit promising mechanical properties similar to those of conventional textile-reinforced mortars, but with a definitely better ductility.
- The application of flax-based textile-reinforced mortars to the strengthening of masonry walls leads to a significant increase in their shear-resisting capacity.
- Textile impregnation as such or coupled with the addition of short plant fibres (pineapple fibres = curauá fibres in this research project) appears to be an efficient strategy to improve the composite material, whose performance becomes similar to - or even better than – that of conventional textile-reinforced mortars, including those containing high-strength fibres.

Outlook

Improving the textile performance through chemical and/or physical treatments, increasing the information about the durability of flax-based textile-reinforced mortars and extending the possible applications in the domain of structural and non-structural members, are as many steps for the success of the proposed sustainable composite materials.

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Original title of the thesis: *Flax TRM composite systems for strengthening of masonry: from the material identification to the structural behaviour*

Supervisors of the thesis: *Professors Enzo Martinelli, Aron Gabor and Carmelo Caggegi*

EFFECTIVENESS OF BASALT FIBRE-REINFORCED CEMENTITIOUS SYSTEMS IN CONFINING MASONRY MEMBERS: AN EXPERIMENTAL INVESTIGATION

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Keywords: masonry, strengthening and repair, basalt fibre-reinforced polymers (BFRPs), basalt fibre-reinforced cementitious matrices (BFRCMs), confinement, RC columns, digital image correlation (DIC), laboratory tests

Introduction

The use of composites based on fibre-reinforced polymers (FRPs) to strengthen masonry columns has become a common practice in the last decades. FRPs, however, exhibit some shortcomings when applied to masonry substrates, due to the organic nature of their matrix. For this reason, increasing attention is paid today to composites based on fibre-reinforced cementitious matrices (FRCMs) [1], in which the polymeric matrix is replaced with an inorganic matrix (such as cementitious mortars). Cementitious matrices guarantee higher breathability and compatibility with the substrate, less sensitivity to debonding at the interfaces, and higher resistance to fire and high temperatures. Moreover, due to the increasing demand for new materials not only mechanically efficient but also sustainable, composites reinforced with basalt fibres are becoming very appealing for strengthening masonry structures.

Several works have been devoted to the application of composites to confine masonry, but only a few are about basalt fibres [2]. Additionally, the small number of studies currently available on the confinement of masonry by means of FRCMs are mainly focused on the efficiency of this system in enhancing the mechanical performance of strengthened members. In fact, few indications are available on the modelling of the compressive behaviour of FRCM-confined masonry [3] and few equations have been formulated to predict structural strength [4]. Last but not least, comparisons on the performance of BFRP and BFRCM systems are still missing in the literature, a necessary step to quantify the effectiveness of cement-based composites in improving the performance of masonry columns.

The aim of this study is the comparative evaluation of the effectiveness of BFRP and BFRCM systems in increasing the load carrying capacity and the ductility of confined masonry columns. Two are the main objectives: to assess the performance of basalt textile as a new material for strengthening applications; and to understand whether composites made with cementitious matrices and reinforced with basalt fibres are a valid alternative to FRPs for strengthening masonry columns.

Experimental programme

In this framework, a detailed experimental investigation is performed by testing BFRP- and BFRCM-confined clay-brick masonry cylinders in compression. A total of twenty-six cylinders were obtained by coring two different assembly schemes (Figure 1), in order to investigate the influence of the number of vertical joints (one or three) in the masonry. Specimens were strengthened by using either one or two layers of BFRP or BFRCM. Unconfined cylinders were also tested as control specimens.

An investigation on the mechanical properties of the constituent materials of the masonry and of the composite, as well as a detailed characterization of the tensile behaviour of BFRCM were performed as a preliminary step. Digital Image Correlation – DIC was used in the tests.

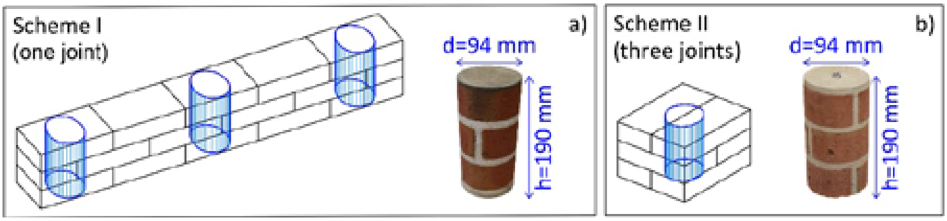

Figure 1. Brick assembly schemes: (a) Scheme I, and (b) Scheme II.

Test results

The stress-strain curves of unconfined and BFRP/BFRCM-confined cylinders are plotted in Figure 2. In Table 1 the average peak axial stress (f_{m0}-f_{mc}), the axial strain at the peak stress (ε_{m0}-ε_{mc}) and the ultimate axial strain (ε_{mu}-ε_{mcu}) are reported, along with the COV values.

Unconfined cylinders exhibit a brittle behaviour, characterized by a steep softening after the peak, while the response of confined specimens is more ductile and has a gentler softening. The average peak stresses for the unconfined cylinders were 25.2 MPa and 19.9 MPa for Scheme I and Scheme II, respectively. In the latter case, the detrimental effect of the vertical mortar joints was sizeable indeed. In general, both strengthening systems improve the bearing capacity of the masonry, with the peak stress increasing with the increase of the reinforcing layers. In particular, the strength gain due to the addition of a second layer was more pronounced in BFRP-confined cylinders. The effectiveness of the confinement was higher for Scheme II (weaker masonry involving three vertical joints), in both BFRP and BFRCM-confined specimens. The number of the joints, however, had a stronger effect in the case of BFRCM-confined cylinders. In the case of Scheme I, considering the cylinders confined with one layer (Fig. 2a), the strength increase with respect to unconfined specimens was comparable in both BFRCM and BFRP-confined cylinders (27% and 29%, respectively), while two layers of BFRP (68% increase) were more effective than two layers of BFRCM (38% increase), see Fig. 2b. BFRP wraps, however, induced a more brittle behaviour with respect to BFRCM (Figs. 2a,b). In fact, the stress-strain curves of BFRP-confined specimens (Scheme I) show a steep softening. On the contrary, BFRCM-wrapped specimens exhibit a more ductile softening, with larger residual strains. Regarding Scheme II, the strength increments yielded by BFRCM are larger than those yielded by BFRP (66% vs 38% for one layer, and 85% vs 71% for two layers, see Figs. 2c,d).

For Scheme II, the two strengthening systems produce comparable peak-strain increments with respect to unconfined specimens, with the BFRP system yielding slightly better results when one layer is used (45% vs 49%) and the BFRCM system yielding slightly better results when two layers are used (75% vs 69%). For Scheme I, BFRCM- wrapping is more effective than BFRP-wrapping with one layer (increments of 59% and 17%, respectively), while with two layers the strain gains are comparable (72% vs 82%).

Considering the average ratio between the ultimate and peak strains in confined cylinders, the best results are achieved in the weaker masonry (Scheme II), for both BFRCM- and BFRP-systems, with gains of 52% and 45% respectively (one reinforcing layer), and gains of 41% and 62% (two reinforcing layers). For Scheme I, similar increments are achieved with one layer of BFRCM (29%) and BFRP (33%), while two layers are more effective using BFRCM than BFRP (37% vs 20%).

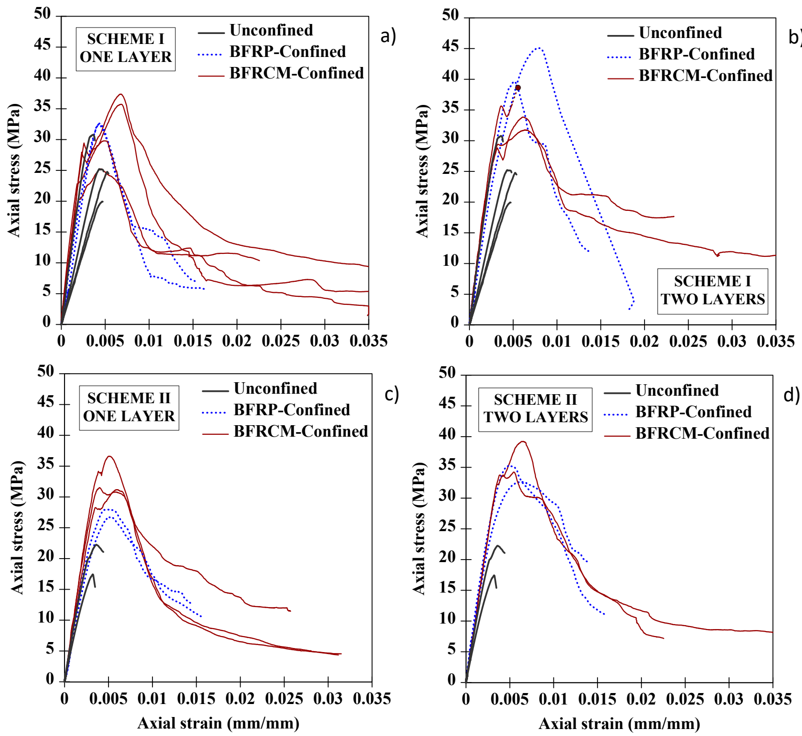

Figure 2. Stress-strain curves on cylinders: (a,b) Scheme I reinforced with one and two layers; and (c,d) Scheme II reinforced with one and two layers.

Table 1. Average results for unconfined and confined cylinders (COV values in brackets).

	Assembly	Confinement	f_{m0}-f_{mc}	ε_{m0}-ε_{mc}	ε_{mu}-ε_{mcu}
	Scheme I	Unconfined	25.19 (17.60 %)	0.0036 (12.41 %)	0.0038 (15.91 %)
	Scheme II	Unconfined	19.85 (17.14 %)	0.0034 (8.88 %)	0.0038 (13.56 %)
FRCM	**Scheme I**	1 layer	32.04 (17.40 %)	0.0058 (21.27 %)	0.0074 (13.37 %)
		2 layers	34.78 (10.35 %)	0.0062 (2.75 %)	0.0085 (6.76 %)
	Scheme II	1 layer	32.98 (9.60 %)	0.0050 (18.78 %)	0.0075 (7.07 %)
		2 layers	36.73 (9.58 %)	0.0060 (12.16 %)	0.0085 (8.90 %)
FRP	**Scheme I**	1 layer	32.56 (0.35 %)	0.0042 (7.08 %)	0.0056 (1.23 %)
		2 layers	42.36 (9.08 %)	0.0065 (31.47 %)	0.0078 (24.73 %)
	Scheme II	1 layer	27.33 (3.21 %)	0.0051 (4.54 %)	0.0074 (1.58 %)
		2 layers	33.95 (5.45 %)	0.0058 (17.90 %)	0.0094 (21.80 %)

The experimental data are instrumental in formulating analytical expressions (not reported here) for the prediction of strength-related parameters in BFRP/BFRCM-confined masonry.

Concluding remarks and outlook

Both basalt fibre-reinforced polymers and basalt fibre-reinforced cementitious matrices significantly increase the performance of masonry cylinders, but BFRCMs are particularly promising for the strengthening of masonry structures. The good performance of this system - compared with the more consolidated retrofitting technique based on BFRP - demonstrates the validity of cement-based systems as an alternative to polymer-based systems, with numerous advantages in masonry strengthening.

The influence that other parameters (type of masonry, shape of cross-section, type of cementitious matrix) may have on the effectiveness of BFRCM strengthening systems requires further studies, inclusive of tests on large-scale columns necessary to understand possible scale effects.

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Supervisors of the thesis: *Professor Livia La Mendola and Dr. Giovanni Munafò*

FABRIC-REINFORCED CEMENTITIOUS-MATRIX SYSTEMS FOR MASONRY STRENGTHENING: EXPERIMENTAL INVESTIGATION AND DESIGN RULES

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Keywords: fabric-reinforced cementitious matrices (FRCMs), basalt/steel micro-fibres, masonry, seismic upgrade, strengthening, sustainability, cyclic tests (in shear-compression), shaking table, design rules

Introduction

Fabric-reinforced cementitious-matrix (FRCM) systems, made of high-strength textiles embedded into inorganic matrices (mainly cement- and lime-based mortars) and externally bonded to structural members, are a sustainable, compatible and cost-effective solution in the retrofitting of existing concrete and masonry constructions. In fact, the high strength-to-weight ratio of FRCM systems allows for a significant improvement in structural capacity with a minimal mass and stiffness increase [1-3].

The growing interest of the scientific and professional communities towards the application of FRCM in structural retrofitting has fostered the development of an increasing number of strengthening systems, nowadays available on the market. Nevertheless, any extended use of FRCM-based reinforcement in engineering practice requires answers on a significant number of issues still open to investigation.

First, for each structural application, the most suitable FRCM system must be identified. Secondly, a deeper knowledge is necessary on the seismic behaviour of FRCM-strengthened structures. Thirdly, design rules should be developed to properly account for the increase of the strength and displacement capacities provided by FRCM-based reinforcement.

This research project is a contribution to the filling of the above-mentioned knowledge gaps, with the focus on the out-of-plane and in-plane strengthening of masonry walls by means of FRCM systems.

Experimental program and analytical models

Three are the main sections of this research work. The behaviour of small-scale FRCM specimens and of full-scale retrofitted structural members is experimentally investigated in the first and second section, respectively. The third section is devoted to the proposal and validation of formulae for the design of structural members strengthened with FRCM.

As a preliminary step, necessary to fully understand the behaviour of the materials, the tensile and bond behaviours of two FRCM systems (containing either a net of basalt micro-fibres or an array of galvanized-steel micro-strands) were investigated.

At the structural level, both the out-of-plane and the in-plane behaviours were explored, the former by means of a shaking table and the latter via cyclic shear-compression tests on FRCM-retrofitted walls. The tests on the shaking table were carried out on two wall specimens (3.48m high, 1.5m wide and 0.25m thick), the first made of regular tuff blocks and the second of rubble stones, subjected to seismic out-of-plane vertical bending, before and after retrofitting with Basalt FRCM- and steel-reinforced grout. Shear-compression tests were carried out on two double-leaf rubble-stone masonry walls (1.2m high and wide, and 0.25m thick), subjected to in-plane shear and compressive forces, before and after retrofitting with basalt FRCM.

Based on the results of the experimental campaign, in order to foster the transfer of knowledge from academy to engineering practice, analytical approaches were proposed as well, for the design of out-of-plane and in-plane strengthening systems based on FRCMs, to be adopted in masonry walls. An extended experimental database was used in the calibration of design formulae inclusive of the increased strength and displacement capacity yielded by FRCM systems, within the design-by-testing approach suggested in Eurocode 0 [4].

This research project highly benefitted from the close interaction with ACI 549-0L Liaison Committee, whose recently-published ACI 549.6R-20 guide [5] in turn is based on some results of this research project.

Results

The direct tensile tests and the shear-bond tests carried out on small-scale FRCM specimens revealed a significant difference in the failure mode exhibited by basalt FRCM and steel- reinforced grout.

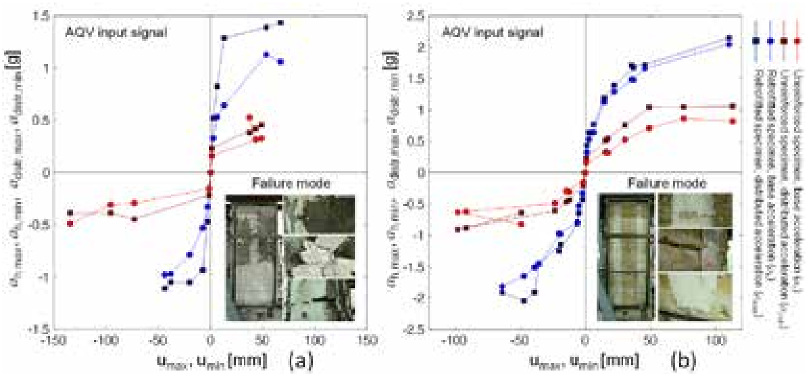

Figure 1. Plots of the acceleration vs. the displacement for a stone wall (a) and for a tuff wall (b), under the seismic input of L'Aquila earthquake (2009).

The shaking table tests proved the effectiveness of FRCM systems in enhancing the out-of-plane flexural strength of masonry walls, for either distributed or discrete reinforcement layouts. In fact, FRCM application may lead to a strength increase close to 1.5 times (Figure 1). The deflection capacity and the initial stiffness of FRCM-strengthened walls turn out to be basically unchanged with respect to that of the unreinforced specimens. Furthermore, FRCM can limit the progression of earthquake-induced damage [6].

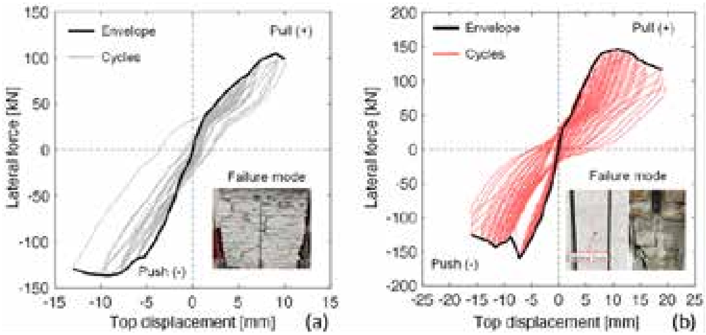

Figure 2. Lateral force vs. top displacement curves for masonry walls.

Smaller but not negligible positive effects of FRCM reinforcement on the in-plane capacity of masonry walls was observed in shear-compression tests (Figure 2). Thanks to FRCM reinforcement, the shear strength, the drift capacity and the initial wall stiffness increased by 35%, 50% and 30%, respectively, as a demonstration of the suitability of FRCM systems for seismic retrofitting [7].

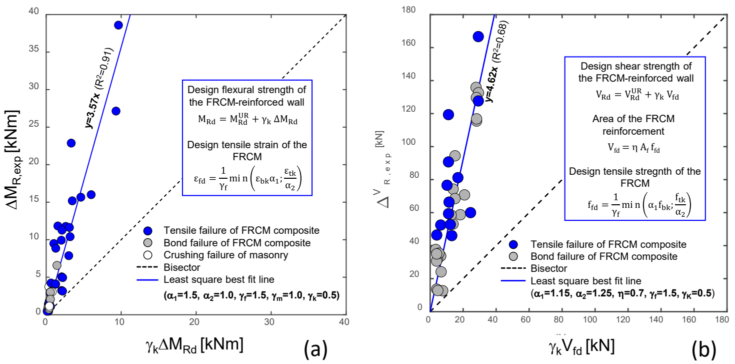

Figure 3. FRCM-retrofitted walls: (a) flexural-strength increase, and (b) shear-strength increase from the tests vs. design values.

As for design equations, a compatibility-based expression is proposed in this study for the structural assessment of FRCM-reinforced walls subjected to out-of-plane bending, whereas a simplified limit analysis-based method is suggested for the preliminary design of the reinforcement (Figure 3a) [8]. For shear strengthening, a simpler purely-additive relationship is proposed to account for the contribution of FRCM and CRM (Composite Reinforced Mortar) systems, as well as to introduce the drift capacity of the retrofitted walls (Figure 3b) [9]. Two coefficients (α_1 and α_2) are also introduced to account for the different boundary conditions experienced by FRCM composites when applied to structural members, with respect to small-scale laboratory specimens. Last but not least, a coefficient γ_k is recommended to guarantee an adequate safety level in the design at the ultimate limit state (Figure 3).

Concluding remarks

FRCM systems are a promising solution for retrofitting existing reinforced concrete and masonry structures, as demonstrated in this research project with reference to the effectiveness of FRCM systems for strengthening masonry walls under either in-plane or out-of-plane seismic loading. The results of an experimental campaign are presented and analytical relationships are formulated for the design of FRCM reinforcement.

Outlook

The long-term behaviour (durability and fatigue) of FRCM systems, the non-destructive test and control methods for condition assessment during the service life, and the combination of structural strengthening and energy saving into integrated systems are among the issues open to further investigation.

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Supervisor: *Professor GianMarco de Felice*

Topic B

R/C AND P/C STRUCTURES

B1 - Testing and Modeling

CRACK MODEL FOR THE CAPACITY ASSESSMENT OF RC STRUCTURES USING NONLINEAR FINITE-ELEMENT ANALYSIS WITHIN THE FRAMEWORK OF PARC SOFTWARE

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Keywords: RC structures, existing structures, nonlinear finite-element analysis, crack model, buckling, 2D modelling

Introduction

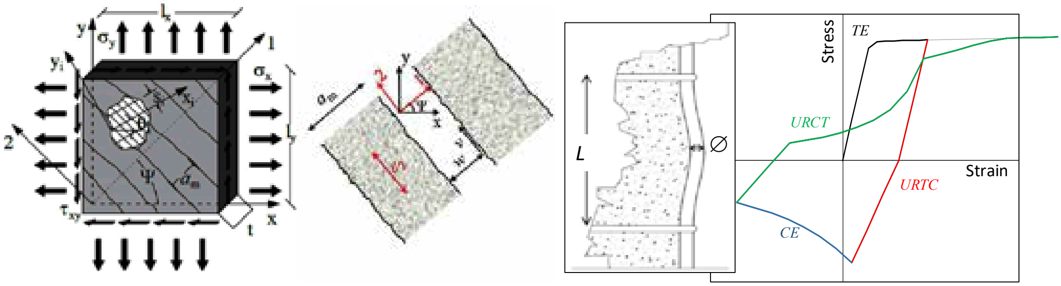
The nonlinear behaviour of reinforced concrete (RC) structures ensues from the highly nonlinear response of the materials to cyclic loading, inclusive of seismic loading. For this reason, realistic cyclic constitutive models are required to describe reasonably well the behaviour of RC members. Existing commercial finite-element codes often have limitations in representing the cyclic behaviour, because of simplistic assumptions on materials properties or the inability to consider certain particular aspects of the failure modes, for example, in existing buildings.

Recent and past seismic events (L'Aquila, April 6th 2009; Finale Emilia, May 20th 2012; Medolla, May 29th 2012; Rieti, August 24th 2016; Norcia, October 30th 2016) highlight the seismic vulnerability of old RC buildings, making the modeling of the existing buildings of primary interest. These structures were typically designed to only resist gravitational loads, without considering earthquake-induced actions. Consequently, the structural members of these buildings are often undersized, lack appropriate structural details and are prone to unexpected collapse modes (seldom found in new buildings) controlled by either concrete brittle failure or longitudinal-bar buckling.

This research project aims to contribute to a correct methodological and engineering approach to predict and describe the collapse mechanisms typical of new and existing structures. In fact, limited attention has been devoted so far to the implementation of deterioration models into numerical codes and mostly with reference to member resistance in existing structures. The need to handle every single constitutive law and to introduce different resisting contributions has recently led to the formulation of a new crack model for RC members, called PARC-CL 2.1 (Physical Approach for Reinforced Concrete in Cyclic-Loading conditions). PARC-CL 2.1 crack model takes into account plastic and irreversible deformations in the unloading-reloading phases, considers the hysteretic cycles of both concrete and steel, and is also suitable for cyclic and dynamic analyses. PARC-CL 2.1 crack model has been implemented as a user’s subroutine into the finite-element code ABAQUS, in order to combine an accurate modeling of materials behavior with a well-known commercial solver. The comparison of the experimental evidence with the results obtained from nonlinear FE analysis (NLFEA), by means PARC-CL 2.1 crack model, demonstrates the efficiency and potential of the proposed model.

Numerical model

PARC-CL 2.1 model is based on a total-strain fixed-crack approach, in which the quantities controlling the problem are the opening *w* and the sliding at the crack interface *v*, as well as the strain in the concrete struts that are located between contiguous cracks, Figure 1a. With reference to the local modeling of cracked reinforced concrete, the above variables make it possible to effectively introduce compatibility and equilibrium conditions, and to include such phenomena as aggregate interlock, tension stiffening, shrinkage and buckling.



(a) (b)

Figure 1. PARC-CL 2.1 crack model: (a) RC membrane element subjected to plane stresses; and (b) buckling of longitudinal bars.

In the previous versions of PARC-CL 2.1, the model by Menegotto and Pinto [1] was introduced to describe steel cyclic behaviour. This model, however, does not include the buckling of longitudinal reinforcement. In order to extend the applicability of PARC-CL 2.1, the constitutive model for steel - inclusive of buckling - proposed by Kashani et al. [2] has been later implemented, Figure 1b.

Buckling reduces the response of the structural member, in terms of strength and ductility. In NLFEA it is possible to include this effect by implementing appropriate constitutive laws for the steel, able to describe the softening behaviour in compression. The yield stress and the slenderness ratio λ (defined as the ratio between the stirrups distance, L, and the longitudinal-bar diameter, ∅) are identified in literature as the most critical parameters governing bar buckling.

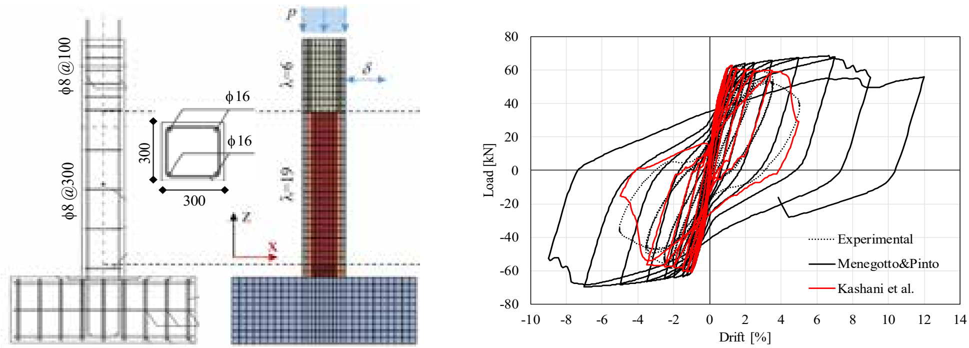
Numerical results

The systematic fitting of the experimental results concerning different types of structural members subjected to monotonic, cyclic and dynamic loading [3]-[4]

confirms the soundness of the formulations implemented into PARC-CL 2.1 and demonstrates the reliability of the proposed analytical tool. The efficiency of the code in the prediction of the structural response of new buildings is the driving force behind the extension of the formulations to existing buildings.

In framed structures, columns are generally the most important structural members. Understanding their seismic behavior is very helpful in the assessment of the structural response of the entire building with reference to deformations, forces and energy dissipation. For this reason, a RC column tested by Meda et al.[5] characterized by poor material characteristics, large stirrup spacing (∅8/300 mm at the column base) and subjected to horizontal cyclic loads was analysed. Further details about column geometry and properties are available in [5].

Four-nodes shell elements with full integration and 3 Simpson integration points for each layer along the thickness were used to model the column, Figure 2a. Since the slenderness ratio of the vertical bars in the lower part of the column is close to 19, buckling phenomena are likely to occur.



(a) (b)

Figure 2. Lightly-reinforced column examined in this research project (a), and experimental/numerical load-drift curves (b).

Figure 2b reports the main result in terms of load vs. drift curves as yielded by NLFEA using PARC-CL 2.1 crack model and two models for steel (inclusive - or not – of buckling, respectively). Figure 2b demonstrates that any steel model not inclusive of buckling is unable to capture the actual ultimate resistance of an RC member (in the column in question the resistance is overestimated by about 60%, and the ductility by about 50%).

Concluding remarks

More refined constitutive laws are needed in order (a) to describe the failure mechanisms typical of the response of existing RC structures subjected to cyclic and dynamic loading, and (b) to make the evaluation of the ultimate load-bearing capacity more reliable. The most-diffused reinforcing-steel constitutive laws, frequently adopted in design practice, can model the nonlinear behaviour of RC columns before buckling- induced failure, but not the detrimental effect caused by any severe buckling in the vertical reinforcement. This may lead to the overestimation of the ultimate capacity in terms of strength and ductility. Realistic constitutive laws for the materials are, therefore, instrumental in modelling RC structures with finite-element techniques, based on 2D or 3D finite elements (brick, shell), or on fibre-based finite-elements. There are, however, simpler models available to the structural designer, as lumped-plasticity models or models based on beam elements, more suitable in case of large structures with many degrees of freedom. In these models, the nonlinear behaviour in bending is defined by means of moment-curvature relationships. The moment-curvature relationships, however, do not generally consider the softening behaviour associated with the buckling of the longitudinal bars. In this sense, modelling with multi-layered shell elements may be a powerful tool able to provide more refined moment-curvature or moment-rotation relationships to be applied when using simplified modeling techniques.

Outlook

The efficiency and potential of the nonlinear FE PARC-CL 2.1 crack model will be the starting point of its application to the description of the seismic behaviour of degraded structures, including those subjected to bar corrosion.

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Original title of the thesis: *PARC-CL 2.1: Crack Model for the Capacity Assessment of New and Existing Reinforced Concrete Structures using Nonlinear Finite Element Analysis*

Supervisor of the thesis: *Professor Beatrice Belletti*

PRECAST TUNNEL SEGMENTS: STRUCTURAL OPTIMIZATION BASED ON HYBRID SOLUTIONS

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Keywords: precast tunnel segments, fibre-reinforced concrete (FRC), innovative reinforcement systems, hybrid systems, laboratory tests, non-linear finite-element analysis (NLFEA).

Introduction

Underground infrastructures have a fundamental role in modern society, thanks to their contribution to the improvement of the mobility of both people and goods, and to the development of new infrastructures. This is confirmed by the construction or extension of new metro and railway tunnels, as well of new service tunnels (for underground pipelines, power systems, sewage, hydropower, etc.) [1]. The growing demand for underground spaces has been met by significant developments in the excavation processes, whose advancement rate - guaranteed by mechanized tunnelling machines (TBMs) - has favoured the technology based on *assembled concrete precast segments* for the final lining. In this way, the construction process has become faster and compatible with the excavation rate [2]. Precast tunnel segments generally require intricate systems of steel bars for the reinforcement. In fact, the bars cage must comply with the natural curvature of the segment and with the presence of various items like bolt pockets and other devices, which hinder the construction of the cage itself. The further need to reduce the production time and the cost of the segments is nowadays arising the interest of researchers and designers towards new reinforcement solutions [3,4]. Within such a framework, this research project aims to contribute to the know-how on innovative reinforcement solutions, meeting the safety and cost-effectiveness requirements of the final lining. The main objective is to assess whether fibre reinforcement in fibre-reinforced concrete - FRC can partially (*hybrid reinforcement*) or totally replace the traditional reinforcement made of steel bars. A further objective is the possible reduction of the lining thickness by adopting new *hybrid configurations* based on high-performance fibre-reinforced concrete (HPFRC) placed in certain specific regions of the segments. To achieve these objectives, laboratory tests (on both small- and large-scale specimens) and nonlinear numerical analyses are required.

Experimental program

This research project starts from the most critical loading conditions for precast-tunnel segments. Many international guidelines [3,4,5] consider the *thrust jack phase*, during the boring stage, as one of the most critical loading conditions for the segments. (The jacks forcing the TBM to advance exert a high axial load on a reduced contact area of the already-built portion of the lining). Accordingly, an in-depth study was developed to investigate partially-loaded areas in FRC members. Initially, the basic features of load spreading into a concrete member were studied by analysing prismatic specimens (without curvature). The experimental campaign was developed by testing 30 specimens, 24 made of steel fibre-reinforced concrete (SFRC) and 6 reinforced with traditional rebar cages. The specimens had a square section of 250 mm side (d) and 750 mm height (h), loaded through a steel plate 100 mm wide (a) and 250 mm long (to represent a line load over a 250 mm length), Figure 1a. In more detail, two different types of fibres (long and short steel fibres) and three different amounts were considered. The effect of fibre orientation on concrete splitting was also investigated by considering two different casting directions. Later, an experimental campaign was carried out on full-scale precast tunnel segments to simulate the loads applied by the boring machine, Figure 1b. To this purpose, the geometry of Scilla tunnel (located in Southern Italy) was considered as a case study. This lining has an internal diameter (D_i) of 3500 mm and a thickness (t) of 200 mm. Each ring consists in four precast tunnel segments 1100 mm long. Firstly, the mechanical characterization of different polypropylene fibre-reinforced concretes (PFRCs) was carried out. Secondly, four reinforcement arrangements for the tunnel segments were devised: a *traditional* reinforcement arrangement consisting of reinforcing bars, two arrangements including only fibres of two types (macro synthetic polypropylene and steel fibres) and a hybrid arrangement characterized by a limited amount of reinforcing bars in combination with macro synthetic fibres. In total, 6 full-scale precast segments were cast and tested under very concentrated loads.

For the same segment geometry and reinforcement arrangements, six segments were tested in bending (Figure 1c) to reproduce the typical stress fields occurring in the production and transient stages.

(a) (b) (c)

Figure 1. Experimental program: (a) line-load test on prismatic specimens, (b) point-load test, and (c) flexural test on precast tunnel segments.

Numerical program

A new concept of hybrid segment was developed starting from the reference geometry of the "Wehrhahn-Linie" of Düsseldorf (Metro tunnel). The main idea is to exploit the opportunity offered by materials with different mechanical properties, within the same structural member, to obtain a reduction in the lining thickness. This reduction, however, may lead to some practical issues in the final phase, when the pressure exerted by the soil causes high lateral/hoop loads to be transmitted through the longitudinal joints, re-proposing the problem of high compressive loads acting on limited areas. Accordingly, a parametric study was carried out to describe the final loading condition, with the focus on the behaviour along the longitudinal joints, Figure 2. A single segment was modelled with appropriate boundary conditions based on the smeared-crack approach, to consider the nonlinear post-cracking properties of fibre reinforced concrete. Compared to physical testing, numerical modelling allows to easily explore different loading conditions and joint configurations, something of great relevance in the initial study of any concrete structure containing hybrid reinforcement.

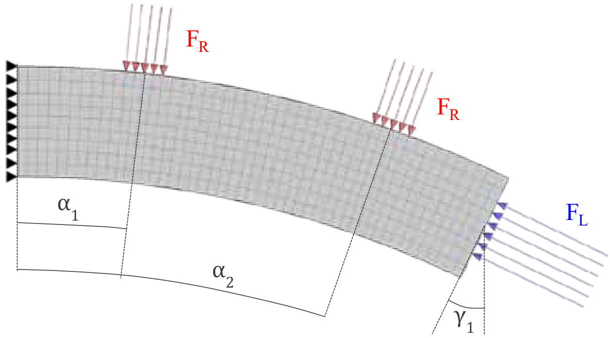

Figure 2. Front view of the 3D model, with the applied radial loads (representing the pressure exerted by the soil), the symmetry-compliant constraints and the lateral/hoop forces acting on the longitudinal joints.

Results

Based on the results yielded by the line-load tests on prismatic specimens, three main stages were identified for the splitting and crushing failures of SFRC specimens. In SFRC specimens the fibrous reinforcement enhances the maximum bearing capacity (from 1.5 to 1.9 times the first-cracking load), and - with $f_{R1m} \geq 4.2$ MPa and $f_{R3m} \geq 6.2$ MPa - a crushing failure may occur, as observed in the prismatic specimens reinforced with traditional bar cages.

As for the load tests on full-scale precast tunnel segments, all the specimens reached the maximum load capacity of the thrust system (2750 kN for each loading shoe). To the contrary, among the different reinforcement arrangements adopted, sizeable differences were observed in terms of local behaviour. Regarding the crack pattern, two common types of cracks were detected, with tangential spalling and tangential splitting cracks, respectively. In PFRC segments, crack opening was up to 2.4 times that exhibited by the reference segment (reinforced with a traditional rebar cage). However, SFRC and RCO+PFRC segments (hybrid arrangement) exhibited a better control of cracking with crack-opening reductions up to 30-35% with respect to the reference arrangement. The tests in bending on precast tunnel segments showed that all reinforcement arrangements satisfy the minimum requirement [4], i.e., a stable flexural behaviour beyond the peak load.

The parametric study indicates also that the hybrid arrangement based on an innovative joint configuration guarantees a bearing capacity slightly larger (+10%) than that of the original segment, even though the lining thickness (300 mm) is 33% less than that of the original segment (450 mm).

Concluding remarks

The results of this research project are meant to improve the understanding on how fibrous reinforcement can control concrete splitting under concentrated loads applied to limited regions. Fibre-reinforced concrete can modify the failure mechanism from splitting to crushing. Fibre-reinforced concrete with adequate post-cracking properties can, therefore, guarantee the same maximum load of traditional reinforced concrete. Accordingly, the development of innovative reinforcement solutions is in progress for traditionally-designed segments characterized by normal-strength concrete and standard thickness.

Even if some research works on full-scale tests of tunnel segments are available in the literature, none of them develops a direct comparison among (a) reinforcement arrangements based on FRC with different post-cracking properties and (b) fibre types in conjunction - or not - with a limited amount of bars. The flexural and point-load tests show that a solution merely including macro synthetic fibres guarantees a barely acceptable bending behaviour and a non-optimal control of the cracks induced by the boring machine. However, if the macro synthetic reinforcement is combined with a limited amount of steel bars (with a reduction of 70% with respect to a traditional arrangement), this *hybrid reinforcement* can provide at the same time a good performance in bending and an effective crack control during the boring process.

Furthermore, segments only made of SFRC (f_{R1m}= 7.5 MPa, f_{R3m}= 8.5 MPa) can guarantee an effective control of the cracks occurring during the excavation and a satisfactory performance in bending. Finally, the concept of *hybridisation* can be brought to a higher level through a different philosophy applied to segment design, by adopting *hybrid segments*, where two concrete types (high strength reinforced concrete and HPFRC) within the same segment are expected to lead to a reduction in the lining thickness compared with traditional segments, without affecting the bearing capacity along the longitudinal joints.

Looking for innovative reinforcement solutions for precast tunnel segments is still an open issue, that will be treated in the continuation of this research project.

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CAST-IN-PLACE FASTENERS IN CONCRETE MEMBERS: PULL-OUT, BEARING PRESSURE AND STRUCTURAL INTERACTION

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Keywords: concrete structures, cast-in-place fasteners, pull-out (of fasteners), bearing capacity (of fasteners), concrete-fastener interaction, cracking, size effect, supplementary reinforcement, displacement-controlled tests, design provisions

Introduction

Construction detailing is the art of transforming thoughts and calculations into real objects. Furthermore, designers and contractors know that poor structural details may bring in an increase in construction costs and even lead to structural collapse.

With this in mind, the importance of fastening technology is obvious. The structural engineer should be familiar with this technology in order to design safe and sustainable structures. Today, thousands of anchorages are used to fasten structural and non-structural components to concrete structures. Depending on the use and on the design loads, both post-installed or cast-in-place fasteners are a suitable and safe solution in construction practice. The need for the re-use and rehabilitation of existing buildings is accelerating the development and the use of post-installed systems. There are, nevertheless, several applications in which cast-in-place fasteners are still preferred. A typical example is represented by hold-down bolts for steel framed structures or for industrial machinery. The use of fastening to concrete is growing faster than the improvement of design and verification methods. In particular, concerning concrete-related failure modes, the current design approach results from a protracted debate regarding the relation between the peak load and the failure surface [1]–[4]. Therefore, design provisions [5] are consistently based on simplified assumptions concerning the control parameters.

Within such a context, this research project aims at providing a further insight on the behaviour of cast-in-place fasteners under tensile loading. Following the technical-scientific literature and looking at many tests and numerical analyses, two key aspects are investigated: (i) the influence of the bearing pressure on concrete cone breakout, and (ii) the structural interaction with the concrete member. With the inherent limitations of a single research study, the results of this research project may contribute to shed light on a few open issues regarding the behaviour of cast-in-place fasteners in relation with the response of the concrete member they are installed in.

Experimental and numerical investigations

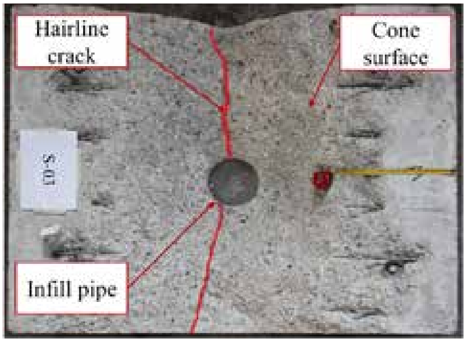
Cast-in-place fasteners of various sizes were tested in very different conditions, during four experimental campaigns consisting in: (i) pull-out tests with different fastener heads, embedment depths and member thickness; (ii) pull-out tests with the fasteners subjected to a confining pressure and embedded in cracked concrete; (iii) pull-out tests on fastener groups; and (iv) pull-out tests on fasteners embedded in *locally-reinforced* concrete.

Numerical analyses complete the experimental study by modelling (i) the presence of free edges, and (ii) the installation in structural members of different thicknesses. The well-known commercial code ATENA was used.

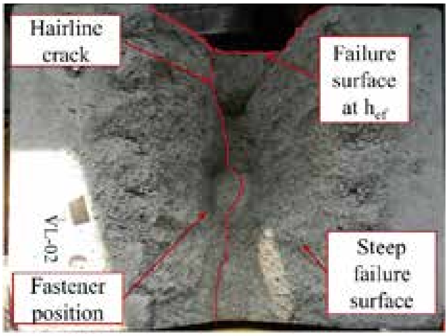
Results

In ideal undisturbed conditions (i.e. member thickness twice as much the embedment depth, and edge distances at least equal to 1.5 the embedment depth), the structural effects – and the load-bearing capacity - are mainly linked to the bearing pressure at the fastener head (Figure 1). The results of specific pull-out tests in unreinforced concrete members show that the collapse is induced by the combination of splitting and bending actions in the concrete. An assessment of the possible structural interaction is feasible through the pull-out tests in cracked concrete. The tests on groups of two fasteners allow to consider the effect of a rough crack intercepting the breakout cone. Pull-out failures occur when cone breakout is prevented by closely-spaced stirrups in the concrete member. The results show also that pull-out failures can be explained through a *fictitious* failure mechanism associated with the accumulation of permanent displacements.

The tests confirm the effectiveness of supplementary reinforcement in preventing concrete cone breakout. The structural response, however, is better predicted by a strut-and-tie model not considered in the current design approach.



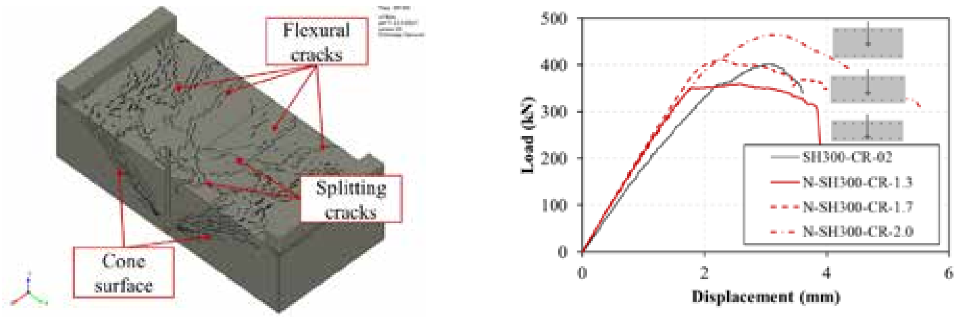
(a)



(b)

Figure 1. Fasteners after testing: (a) very high bearing pressure under the head, and (b) very low bearing pressure.

The analysis confirms that numerical modelling is a valuable alternative to laboratory tests in terms of cost and time. Furthermore, a continuum-based approach can be successfully adopted provided that an appropriate strategy is used to model the cracks intercepting the fasteners (Figure 2).

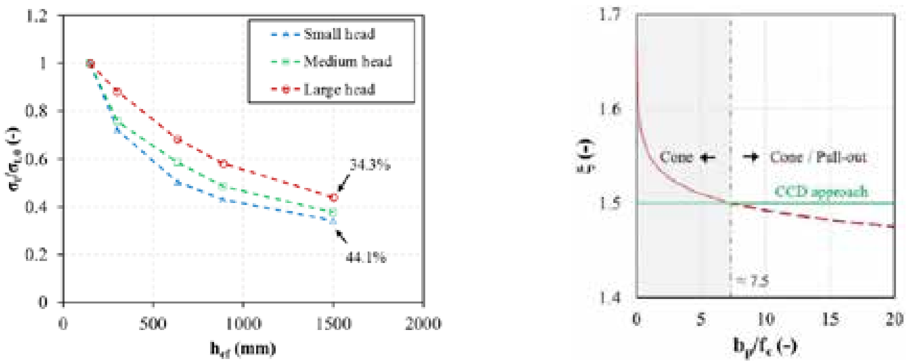


(a) (b)

Figure 2. Results from the numerical analysis (cracking included) for various values of member thickness: (a) crack pattern, and (b) load-displacement curves.

Concluding remarks

A new refined approach is proposed to evaluate the bearing capacity of a single fastener. The approach combines concrete cone breakout and pull-out failure in a single equation, the two mechanisms being connected through the bearing pressure. The model was calibrated on the basis of data available in the literature. Since (i) neglecting size-effect leads to unconservative predictions and (ii) CCD approach [5] is too conservative for large-size fasteners, the numerical study of Ožbolt et al. [6] was taken as a reference for the behaviour of large-size fasteners (Figure 3a). Therefore, the model proposed by Furche [7], [8] was extended to fasteners other than headed studs, by introducing a different exponent in the expression for the bearing capacity as a function of fastener embedment length (ξ in Figure 3b). In this way, the shape of the failure surface is taken into account and the role of size effect is somewhat weakened by introducing the relative bearing pressure under the fastener head (b_p/f_c in Figure 3b).



(a) (b)

Figure 3 – (a) Results from numerical analyses performed by Ožbolt et al. [6] about the relative concrete cone resistance, and (b) exponent ξ vs. relative pressure.

Finally, design recommendations are suggested considering two levels of approximation: *level I* based on a rather classic *force-controlled* design philosophy, and *level II* based on a rather innovative *displacement-controlled* design philosophy.

Outlook

This rather comprehensive study on cast-in-place fasteners embedded in RC members is mainly about the behaviour under tensile loading in conditions never experimentally investigated so far, to author's knowledge. The results of the pull-out tests show that (i) splitting action remains a major risk for the load-bearing capacity of cast-in-place fasteners, and (ii) lowering the bearing pressure under the head of the fastener leads to an increase in the load-bearing capacity, something not predicted by the current design approach. On this basis, design recommendations are formulated and - among others - a new design equation is proposed to evaluate the bearing capacity controlled by either cone break-out or fastener pull-out.

The key findings of this research project may be useful in addressing further efforts to clarify some peculiar aspects of the complex combination among boundary conditions, embedment length, pressure underneath fastener head and failures modes typical of cast-in-place headed fasteners.

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Original title of the thesis: *Pull-out of Cast-in-Place Fasteners, Influence of the Bearing Pressure and Structural Interaction with the Concrete Member*

Supervisors: *Professors Giovanni Muciaccia and Giampaolo Rosati*

Topic C

EXTREME CONDITIONS

SEISMIC RESPONSE OF CONCRETE FAÇADE SYSTEMS IN REINFORCED-CONCRETE PREFABRICATED BUILDINGS

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32nd Cycle of the PhD Course in
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Keywords: RC precast panels, cladding panels, panel-structure connections, out-of-plane connection capacity, testing, seismic response, shaking table

Introduction

The last seismic events that struck Italy and southern Europe, in particular, L'Aquila in April 2009, Lorca 2011, Emilia in May 2012 and Central Italy in 2016, caused the collapse or the damage of a great number of industrial precast buildings. Among the main causes of those structural collapses, four were identified: (i) lack or insufficiency of connection between structural members; (ii) structural inadequacy of the columns, in terms of lateral resistance and ductility; (iii) cladding members (panels) not well connected to the structure; and (iv) unbraced racking units carrying heavy items, that can fall and damage the main structure.

Many aspects related to the above-mentioned issues have been addressed in national and European studies within SAFECAST [1] and SAFECLADDING [2] research projects aimed at (i) investigating the seismic behaviour of precast structures with cladding wall panels by means of tests and numerical analyses, and (ii) developing innovative connection devices together with new design approaches.

In-plane seismic response of cladding panels

Within this context, the results from a shaking-table experimental campaign, performed at the University of Ljubljana [3] were analysed, to study the seismic response of single-storey RC precast buildings with vertical panels. The main parameters under investigation included the type of the connection between the panels and the main structural system of the building (long or short hammer-head straps) and between the panels and the foundation (fixed or rocking panels).

Numerical models were formulated and implemented into the OpenSees software [4]. These models were able to closely fit the experimental results concerning both fixed and rocking panels, thanks to the implementation of the hysteretic laws of the connections [5]. In the case of rocking panels, a hysteretic model capable of describing the impact between the panel and the foundation was also introduced and calibrated.

Later, at the Laboratory of Tests and Materials of the University of Florence [6] an experimental campaign was carried out on the characterization of off-the-shelf steel hammer-head strap connections (called “Standard” in the following) and of innovative connections (called “SismoSafe”). During the tests, “Standard” connections exhibited a hysteretic behaviour until the collapse triggered by the flexural failure of the strap. On the contrary, no damage occurred in the various components and in the channel profiles of the “SismoSafe” connections, where the force is mainly transmitted by the friction activated during the sliding process between the two guide rails (Figure 1a,b).

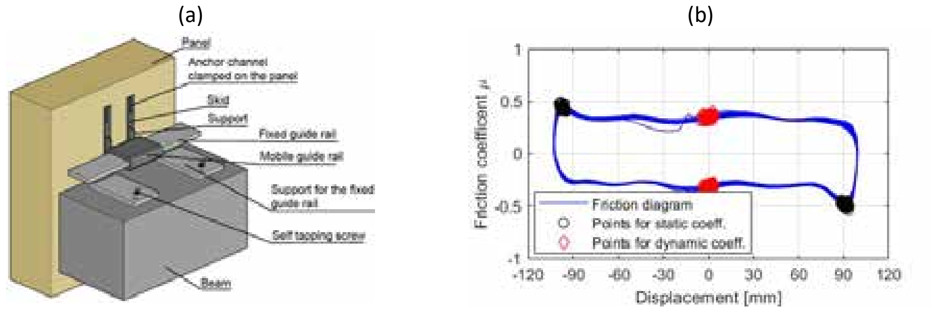

Figure 1. SismoSafe connection: components (a); and frictional behaviour (b).

Out-of-plane response of cladding panels

The out-of-plane behaviour of “Standard” hammer-head-strap connections and “SismoSafe” connections were experimentally investigated [7]. The tests show that Standard connections (Figure 2a) have a lower out-of-plane resistance than SismoSafe connections (Figure 2b), as - on panel side – the former connections exhibit an ultimate resistance about three times lower (15 kN) than SismoSafe connections (45 kN) under both cyclic (C) and monotonic (M) loading.

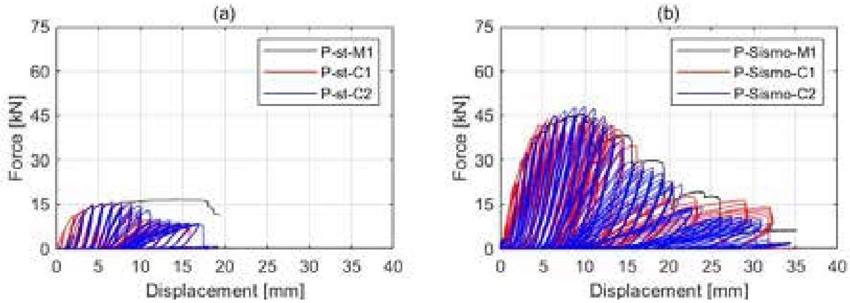

Figure 2: Out-of-plane force-displacement curves for: (a) hammer-headed strap connections; and (b) SismoSafe connections.

The out-of-plane seismic demand for non-structural members can be determined by applying an equivalent static force calculated with the formulation of the floor spectra [8]. However, this formulation is not appropriate for vertical panels placed at the ground level, since they are directly stressed by the seismic acceleration and also by the action coming from the structure above. To understand what might be the out-of-plane force that stresses the panel-structure connection, a parametric analysis has been performed to study the relationship between the forces transmitted by the connection calculated on the structure F_{real} (a) and in the case of an infinitely stiff structure F_{rigid} (b), respectively.

The input-parameters of the analysis were a series of i-values of R_M (ratio between the mass on the structure and the mass of the panel) and j-values of R_T (ratio between

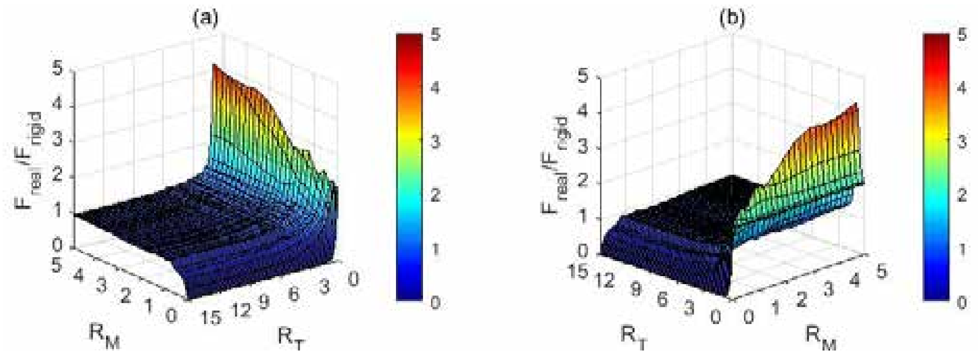

Figure 3. Results from the 3D parametric analysis: (a) south-west view, and (b) south-east view.

the period of the structure and the period of the panel). The results of the parametric analysis, in terms of R_T, R_M and F_{real}/F_{rigid}, are represented by a 3D surface (Figure 3a,b).

If the ratio R_T is close to 1.00, there is an amplification, up to 4 times, of the force F_{real} with respect to the force F_{rigid}. Finally, an analytical formulation for the surface was proposed as an alternative to the floor spectra considered by the Eurocode 8 [9].

Parametric study on the seismic response of panel-to-structure connections

A parametric study was carried out to understand in which cases panel-to-structure connections do not provide sufficient seismic safety. Numerical analyses considered the simultaneous presence of in-plane and out-of-plane seismic loads. The structures under investigation differed for the roof mass (20 to 100t) and the height of the columns (5, 7 and 9m). The influence of the ratio between the number of columns and panels was also considered by the factor k_v. The results (Figure 4a,b) show that the seismic demand depends on the vibration period of the structure and that the connection displacement demand increases linearly with the fundamental vibration period of the structure T_1. This applies to the structures with the panels either fixed to the foundation or subjected to rocking. Furthermore, the out-of-plane force capacity is reached for significantly-higher peak-ground accelerations - PGAs than the failure PGAs of in-plane displacement.

Concluding remarks and outlook

The good performance of SismoSafe connections, in terms of in-plane and out-of-plane behaviour, allow to conclude that these connections guarantee a higher level of seismic safety in precast RC buildings compared with standard connections. Furthermore, in standard connections the in-plane behaviour of the panels is always critical, whatever the configuration at the panel’s base might be.

Further tests tests will be necessary to define displacement-related capacity limits for the SismoSafe devices and to investigate the effect of possible installing imperfections.

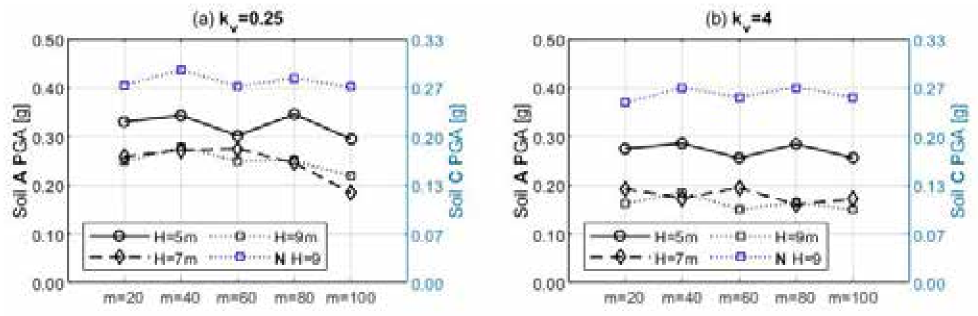

Figure 4. Failure PGA values for in-plane displacement (black) and out-of-plane force (blue): (a) k_v ratio equal to 0.25; and (b) k_v ratio equal to 4.

The interaction between the panels at the corners of the building, and that between the panels and the main columns is another issue worth investigating.

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Original title of the thesis: *Seismic Response of Vertical Concrete Façade Systems in Reinforced Concrete Prefabricated Buildings*
Supervisors: *Professors Andrea Vignoli (UniFi), Maurizio Orlando (UniFi) and Tatjana Isaković (University of Ljubljana)*

NUMERICAL MODELING OF MONOTONIC AND CYCLIC BEHAVIOR OF EXTERIOR RC BEAM-COLUMN JOINTS

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33rd cycle of the PhD Course in
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Keywords: RC beam-column joints, shear capacity, nonlinear numerical analysis, monotonic loading, cyclic loading

Introduction

The vulnerability of exterior beam-column joints in existing RC buildings is a key aspect of the structural behavior under seismic loading. Observations after recent earthquakes indicate that a substantial damage may result from beam-column joints in older-type non-seismically designed frame structures, often leading to undesirable brittle-failure mechanisms. Such a situation is strictly related to the lack of attention in the past to beam-column joints, that were designed without specific concern about structural details. As a result, the seismic assessment of existing RC buildings must be primarily aimed at beam-column joints, by correctly evaluating their local strength- and deformability-capacity.

Different theoretical models are available today to predict the shear capacity of the joints, mainly involving calibration processes based on experimental databases. In spite of their being a valuable tool, these models are mostly empirical and their use may lead to questionable values in terms of shear strength and deformability.

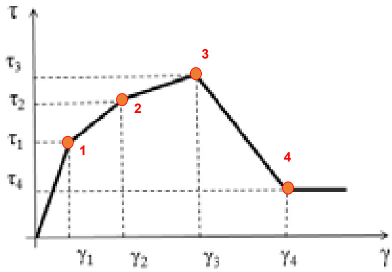
Numerical modelling

The behavior of exterior RC beam-column joints subjected to seismic actions is numerically investigated in this research project, by using a macro-modelling approach. From a phenomenological point of view, the shear behavior of exterior beam-column joints can be described in the following way: a cracking process, the attainment of the peak strength, a subsequent process of strength degradation until the attainment of a residual capacity in shear. Such chain of events can be modelled by means of a multilinear shear stress-strain (τ-γ) constitutive law (Figure 1a), that is defined by four characteristic points (τ_1, τ_2, τ_3, τ_4 and γ_1, γ_2, γ_3, γ_4).

Among the several analytical models available in literature for the evaluation of the shear strength τ_3, (indicated as τ_{max}) the following models have been selected: *model 1* by Kim & LaFave (2012), *model 2* by Vollum & Newman (1999), *model* 3 by Ortiz (1993), *model 4* by Hwang & Lee (1999), *model 5* by Jeon (2015) [1]. For the shear stress at cracking (τ_1), the formula proposed by Uzumeri (1977) was adopted, while for the other stress parameters (τ_2, τ_4) and the four strains (γ_1, γ_2, γ_3, γ_4) the following models have been considered: *model A* proposed by De Risi et al. (2016), *models B1 and* B2 by Celik and Ellingwood (2008), *models C1 and C2* by Shin and LaFave (2004) and *model D* by Sharma et al. (2011) [1].

The above models are combined together to reproduce the shear response (τ-γ) of the *panel zone*. In particular, the shear strength τ_3 given by each of the *models* 1, 2, 3, 4, 5 is combined with the other parameters given by *models* A, B1, B2, C1, C2, D. As a result, a total of 30 τ-γ relationships were implemented in the numerical analyses.

The proposed macro-modelling approach adopts also the so-called "*scissors model*", which consists of a rotational spring connecting a master node and a duplicated slave node located at the same position in the middle of the panel zone (Figure 1b). In order to introduce the contribution of the fixed-end-rotation due to the slip of the longitudinal bars of the beam, an additional nonlinear rotational spring is introduced at the interface between the panel zone and the adjacent beam.



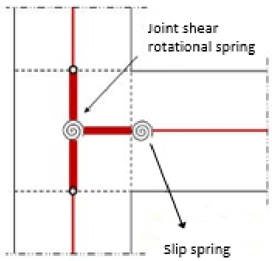


Figure 1. Multilinear τ-γ constitutive law (a); and sketch of the "scissors model" (b).

Nonlinear analysis and results

The aim of numerical analysis, carried out by using the software "OpenSees", is to assess the reliability of the above-mentioned laws in reproducing the experimentally-investigated monotonic behavior of the beam-column joints. A set of 15 specimens well-documented in the literature have been considered. In each case, the monotonic behavior was studied by adopting 30 τ-γ constitutive laws. The results were compared with the envelope of the experimental hysteretic cycles, in terms of applied force vs. drift. The monotonic analyses defined the combinations of the models that better describe the behavior of the specimens during the tests. Models *5A, 1A* and *5C1* provided the lowest percent errors with values of 20.04%, 21.01% and 23.65% respectively. As an example, the numerical and experimental envelopes under monotonic loading are plotted in Figure 2a for a case-study specimen.

Furthermore, a formula able to predict the shear strength of beam-column joints, characterized by a greater precision with respect to the models taken from the literature, is proposed based on a multivariate linear-regression approach. Then, the other stress and strain parameters of the multilinear τ-γ law are derived from a sensitivity analysis carried out based on the ranges proposed in the models taken from the literature. The results obtained by adopting the proposed constitutive law are affected by an error of

15.86%. Figure 2b shows the monotonic curve obtained by implementing the proposed constitutive law in the fitting the reference test.

The proposed constitutive law is also used to perform cyclic analyses, which require the introduction of several parameters related to the *pinching4* uniaxial material model adopted for the shear behavior of the joints. Starting from a proper damage law, a calibration process was carried out to appropriately define the ranges of these parameters, describing the unloading-reloading path of the cyclic curve, as well as the strength and stiffness degradation and the pinching effect.

The numerical-experimental agreement is satisfactory (Figure 3).

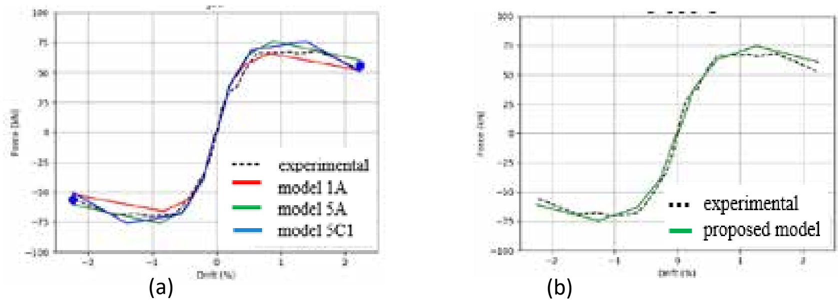


Figure 2. Numerical vs. experimental curves in terms of monotonic envelope: literature models (a) and proposed model (b).

Finally, the proposed model for exterior joints was used to investigate the role that beam-column joints have on the seismic performance of a 2D RC frame selected from the literature [2] and representative of the design approach limited to gravity loads commonly adopted in Italy in the seventies and eighties of the past century. Two approaches have been used to model the frame: the first approach does not introduce beam-column joint elements and, thus, rigid links connect beams and columns. The second approach includes the proposed model to describe the shear behavior of the joints. Pushover analyses prove that the model accounting for joint modelling is able to accurately reproduce the observed nonlinear behavior of the frame. The resulting capacity curves (in terms of base shear vs. displacement) are depicted in Figure 4 for the two approaches (“wJ” for the second approach with deformable joints, and “noJ” for the first approach with stiff joints).

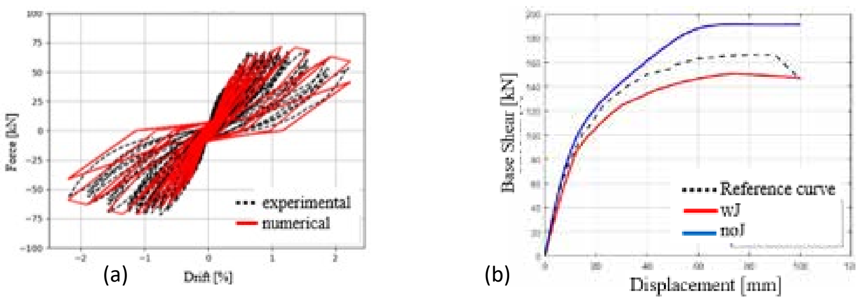


Figure 3. Numerical vs. experimental cycles (a); and pushover capacity curves - 2D RC frame (b).

Concluding remarks

In this study, the *scissors model* is used to reproduce the main phases of the shear behavior of a set of 15 beam-column joints, whose tests are well documented in the literature. Through monotonic analyses, the set of the most efficient models describing the various aspects of beam-column joints is identified. As a result, a refined constitutive τ-γ law is formulated for the panel zone of the joint, in conjunction with a calibration procedure aimed at defining an appropriate set of pinching parameters, as required to carry out cyclic analyses. The proposed model provides is more efficient than literature models, in terms of monotonic envelope and cyclic behavior. The validation of the model is performed by fitting the test results concerning a well-documented 2D RC frame designed according to old-type Italian code provisions (not inclusive of the lateral loads).

With respect to other similar literature models, the model proposed in this study is characterized by the following advantages: (*a*) easy implementation accompanied by a very accurate description of both the monotonic and cyclic responses, in very good agreement with many experimental tests performed on beam-column joints, and (*b*) great robustness and reliability since the model has been calibrated on many tests on RC joints.

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Original title of the thesis: *A Proposal for the Numerical Modeling of Monotonic and Cyclic Behavior of Exterior RC Beam-Column Joints*

Supervisor: *Professors Maura Imbimbo (University of Cassino and Southern Lazio) and Ernesto Grande (University Guglielmo Marconi, Roma)*

ON THE ROLE OF MATERIALS' PROPERTIES AND STRUCTURAL CONTEXT IN REINFORCED-CONCRETE MEMBERS EXPOSED TO NATURAL FIRES

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Keywords: natural fires, cooling, numerical modeling, sectional analysis, finite element analysis

1 Introduction

The focus of the current fire-design practice is limited to the heating phase of a fire and very little indications are given on the behavior during the cooling phase and after the fire. Nowadays, however, structural fire design is changing, as it is moving from the traditional approach, based on the standard fire, to a performance-based approach with a more accurate representation of real fires, leading to structurally safer and more cost-effective solutions.

Modelling the cooling phase certainly involves many difficulties, but allows to cover a wider range of situations of practical interest, in comparison to standard fire, like structural failures in the cooling phase [1], and the residual behavior of the structures surviving the full heating-cooling cycle (a major issue in structural post-fire assessment). There is, however, no consensus on how to model fires involving heating and cooling.

This research project deals with the structural analysis of typical reinforced- and prestressed- concrete beams and columns, based on three different modelling approaches: sectional analysis, finite-element analysis via beam elements, and the same as before but with 3D elements. With the focus on the cooling phase, the aim is twofold: (a) to investigate the role of materials properties on structural behavior; and (b) to provide an overview on the modelling strategies, with specific reference to the cooling phase.

2 Materials' properties during cooling

2.1 Concrete

The irreversibility of thermal dilation is one of the peculiar features of a full heating-cooling cycle. The maximum temperature governs the amount of the residual elongation and the thermal damage. Based on undisputed evidence (Franssen, 1993, see the thesis), the residual thermal deformation of the concrete is sizeable for temperatures in excess of 500°C.

Accounting for the cooling phase in a constitutive model implies several peculiar issues to be addressed. The constitutive law for concrete in compression should be suitably modified in the case of natural fires; in more detail, the possibility of unloading should be explicitly included (EC-2, 2005). This assumption complies with the fact that transient and creep strains (occurring in the concrete upon first heating) are not recovered during the unloading process, and are not present at all when the residual behavior of concrete is considered. As for the thermal damage, during the heating phase the stress-strain curves are adapted to take care of the decreasing compressive strength and increasing deformability. During the cooling phase, the parameters of the stress-strain curves are not updated.

2.2 Steel

The evolution of the stress-strain law at any given point of the structure is governed by the maximum local temperature and by the load history. The decay of the steel strength at yielding and of the elastic modulus is assumed as per EN 1992-1-2 (2005) and irreversible for temperatures in excess of 500°C (the thermal strain is taken as fully recoverable).

3 Sectional Analysis

The first step of a sequentially-coupled thermo-mechanical analysis is to perform a 2D thermal analysis of the section (here performed by means of the software ABAQUS 6.16). The output consists of the local temperature values and is used as an input in the subsequent mechanical analysis, where the mechanical properties of the materials are introduced as a function of the temperature (something valid also in other numerical approaches).

The objective of the mechanical analysis is to obtain the deformations (axial strain and curvature) of the section as a function of time. As for sectional analysis, the required iterative procedure was implemented into a purposely-developed Visual Basic code, that enables the deformation history to be traced over the whole fire duration.

Sectional analysis is performed on two typical prestressed-concrete sections, as well as on several reinforced concrete beams tested at Michigan State University [2] and exposed to natural fires. Parametric analyses are also performed to study the influence of the major parameters controlling the thermal field, as well as the static and kinematic fields. In addition, sectional analysis (based on the nominal-curvature method, Annex B3, EN 1992-1-2) is extended to a number of columns, whose tests are well documented in the literature.

4 Nonlinear structural analysis via beam finite elements

To overcome the intrinsic limitations of sectional analysis and to offer a more general approach to study simple structural members exposed to a fire, an ad-hoc nonlinear 1D FE code based on RC beam elements (Malerba, 1998) has been developed in Visual Basic for the mechanical analysis of heated members. Both materials and geometric nonlinearities are taken into account, by introducing realistic stress-strain laws (inclusive of the softening behavior), and second-order effect. Several significant examples based on real-scale fire tests on columns are modeled, with their different heating, loading and boundary conditions. The objective is to calculate the time-related evolution of the nodal displacements of the member during a fire. At each time step, the code keeps track of both the temperature history (through the increments of the nodal temperatures*)* and the deformation history (through the strain increments at each node compared with the strain from the previous time increment) - to ascertain whether loading or unloading is under way, a critical aspect in the choice of the appropriate stress-strain relationship to be adopted at the given step.

Many realistic parameters characterizing the full heating-cooling are included. Among the many, transient creep is introduced both explicitly [3] and implicitly.

5 3D Finite Element Analysis

Sequentially-coupled 3D finite-element thermo-mechanical analyses are performed by means of the commercial finite element software ABAQUS 6.16. Two sub-models have been formulated: a model for thermal analysis (inclusive of bars and stirrups) and a model for mechanical analysis. Nodal temperatures in the member, obtained from 3D heat-transfer analysis, act as thermal body-loads in the structural model, being the initial condition for the subsequent mechanical analysis.

In the cooling phase, the mechanical properties are considered as irrecoverable, to account for the thermal damage in the material. This has been done by implementing a FORTRAN user subroutine - UFIELD, which updates the mechanical properties only in the heating phase. The introduction of materials properties in Abaqus requires the definition of the temperature-dependent elastic-plastic properties. The constitutive models available in ABAQUS have been used to model both concrete and steel, namely an elastic-fracturing model for concrete and an elastic-perfectly plastic model for steel. 3D stress/displacements elements have been used for the discretization of concrete and bars. Concrete-bar bond is assumed to be perfect (no bar slip). The model was validated against available experimental data on RC beams.

Parametric analyses were also performed on RC beams, to investigate the structural role of the major parameters.

Modelling a number of RC columns tested at University of Edinburgh (MacLean, 2018) was instrumental in checking whether the 3D model can reliably predict the deflections in case of exposure to localized non-uniform heating. Finally, hinged columns and simply-supported beams well documented in the literature were analyzed as well.

6 Results

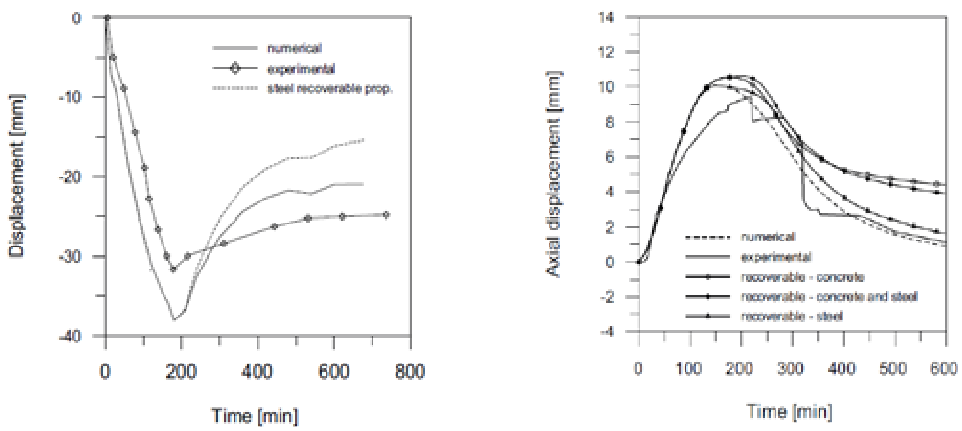
6.1 Irrecoverability of the thermal damage

Figure 1a deals with steel recovery in two RC simply-supported beams [2]. The maximum temperature in the bars - close to 540°C - was reached during the cooling phase. At such high temperatures, sizeable creep strains are expected to develop and steel properties will not be recovered upon cooling. Neglecting the thermal damage in the bars leads to non-conservative displacement predictions.

The diagrams of Figure 1b are about the influence that the strength and stiffness recovery in the concrete and in the bars have on the structural response of a fire-exposed RC column [4]. Assuming full mechanical recovery upon cooling leads to displacement-time responses that greatly differ from test results. The influence of concrete markedly prevails over that of steel, as demonstrated by the fact that the curve based on full concrete and steel recovery (dash, "numerical") closely fits the curve solely based on steel recovery (solid triangles).

6.2 Comparison among different analysis methods

The mid-span displacement of Beam B2 [2] is very accurately predicted by the 3D model, in both the heating and cooling phase (Figure 2a), while sectional analysis overestimates the peak displacement and underestimates the residual displacement. On the whole, the two methods lead to similar results. In the case of columns (Figure 2b), sectional analysis yields the most conservative prediction for the axial deformation, while the results of 3D analysis are the closest to test results. In Figure 2c, the axial displacement yielded by 3D analysis closely matches the test. The three analyses confirm the time to failure indicated by the test.

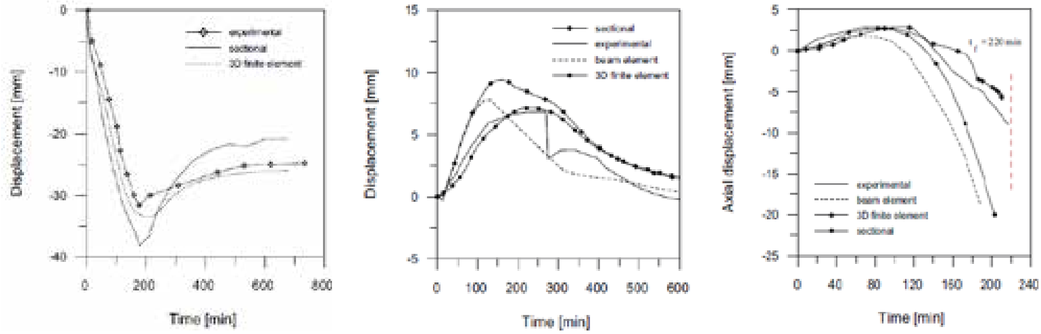


(a) (b)

Figure 1. (a) Displacement evolution for Beam B2 [2]: steel mechanical properties are assumed as irrecoverable (label "numerical") or recoverable, upon cooling; and (b) axial displacement for column C1 [4] – role of the recovery of the damage in the materials.

7 Conclusions and outlook

A realistic representation of the expected fire scenario is instrumental in correctly predicting the maximum temperatures reached inside an RC member, and structural safety should be checked by introducing the cooling phase, when the maximum temperature is generally reached, and the mechanical properties of concrete and steel are not completely recovered.



(a) (b) (c)

Figure 2. Comparison of the different analysis methods for: (a) Beam B2 [2]; (b) Column C1 [4]; and (c) high-strength column tested in Raut and Kodur (2011).

All three models/approaches adopted in this study yield a rather accurate prediction of the structural response, in both the heating and the cooling phase. Sectional analysis is generally conservative in the prediction of time to failure, if materials' properties as a function of the temperature, geometric nonlinearities and irrecoverable damage in the materials are introduced. Beam-element analysis is half-way between sectional and 3D analyses in terms of complexity, but has more applications than sectional analysis. 3D modelling does not have intrinsic limitations in terms of applicability, but its complexity may not be justified in rather simple cases.

The residual properties during the cooling phase – inclusive of the thermal strain – and the passage from single members to structural assemblies are two critical issues still requiring further investigation.

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CHLORIDE-INDUCED CORROSION AND DESIGN IMPLICATIONS IN FIBRE-REINFORCED CONCRETE STRUCTURES

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Keywords: fibre-reinforced concrete, durability, chloride-induced corrosion, pitting corrosion

Introduction

The corrosion of rebars in cracked reinforced-concrete (RC) structures has been investigated by several authors [1, 2, 3], who express a general consensus on the reduction of the initiation period in cracked concrete, compared to uncracked concrete (where both concrete quality and cover depth are the most important parameters). There is no agreement on the influence of crack width on the propagation of the corrosion [4, 5], while scholars agree on the negative effects that cracks have on the long-term behaviour of RC structures when certain values of crack width are exceeded. For such a reason, international standards prescribe limits to crack width, based on service-life requirements and exposure conditions.

The use of fibre-reinforced concrete (FRC) in structural members definitely improves crack control at the Serviceability Limit State (SLS) [6, 7], with more diffused cracks, that are thinner and closer compared to RC members without fibres. At the Ultimate Limit State (ULS), fibres may be useful as shear reinforcement [8]. Some doubts, however, concern the possible negative influence of fibres on structural ductility in bending, because of crack localisation [9]. As for the influence of fibres on bar corrosion, most studies deal with the uncracked stage with the focus on concrete permeability. According to some of these studies, fibres do not modify concrete permeability and the rate of chloride ingress into the bulk matrix [10]. On the contrary, in the cracked stage a reduction of permeability in cracked regions has been observed in FRC specimens [11, 12]. In a recent work by Berrocal [13], however, relatively-low fibre dosages (< 1% by volume) have been shown to improve corrosion resistance since fibres tend to delay corrosion initiation and to reduce corrosion rate. On the whole, fibre influence on the corrosion rate in the reinforcement is still not well understood, as test results are few and contradictory. Fibres may also reduce corrosion-induced longitudinal cracking and cover spalling, even at high corrosion levels, thanks to the bridging effect that fibres have on cracks.

Galvanic cells may also form between the bars and the fibres, but there is no general consensus on this issue.

Experimental programme

In this context, a research project was carried out to investigate chloride-induced corrosion in cracked RC and FRC members. Sixteen tension ties – equally subdivided between RC and FRC - were cast to assess their mechanical behaviour after the exposure to aggressive environmental conditions. In the FRC ties steel fibres were used and their amount was 50 kg/m^3 (SFRC50, v_f = 0.64% by volume). All specimens had the same dimensions (90x90x830 mm), were reinforced with a single steel bar (Ø12 mm) and underwent wet-and-dry cycles for 280 days in a water solution containing 50 g/l of sodium chloride. During the immersion in the solution (= corrosion period) the specimens were subjected to a constant load typical of service conditions, in order to keep the ties in cracked conditions as close as possible to real conditions. The length of the specimens was chosen in order to have at least 4-5 cracks in each tie.

Three tension ties of each mix were tested up to a strain of 5‰ (beyond the elastic limit) in order to monitor the overall response in tension. A clear difference between RC and SFRC50 specimens was observed, as expected. The load at first cracking remains similar in RC and SFRC50 specimens, as well the uncracked branch. In the cracked stage (after crack formation and stabilisation), fibres bring in a remarkable increase in the general stiffness due to stress transfer across cracks (tension stiffening). Crack stabilisation started around 28 kN in RC and around 30 kN in SFRC50 specimens, which correspond to a tensile stress on the bars close to 250-270 MPa. As expected, the mean crack spacing in SFRC50 specimens was smaller than in RC specimens, this being one of the major benefits yielded by fibres, since the smaller the crack spacing (i.e., more cracks), the thinner the cracks. In particular, after crack stabilisation, crack spacing (s_{rm}) was 173 mm and 135 mm for RC and SFRC50, respectively. No significant splitting cracks were observed before the yielding of the reinforcement.

The corrosion tests were carried out on the remaining specimens (i.e, 5 for each mix) under a constant tensile load, to keep the specimens in cracked conditions (i.e., to keep the cracks open) during each corrosion test. In particular, the specimens were precracked by using an Instron Machine (applied load equal to 34 kN, corresponding to a tensile stress in the bars equal to 300 MPa). In this way, the specimens exhibited a stabilized crack pattern, and crack formation and width were monitored. Crack width was measured by means of an optical microscope, and the maximum values were 0.19 mm (CV = 0.11) and 0.11 mm (CV = 0.15) in RC and SFRC50 tension ties, respectively. It is worth mentioning that these values are very close to those usually found in cracked RC structures in service conditions.

After cracking, the specimens were placed inside a stiff steel frame, where they were reloaded to 34 kN. Afterwards, the frames and the loaded specimens were immersed in a sodium chloride solution of 5% (i.e., 50 g/l of NaCl), ready to be subjected to 40 wet-and-dry cycles (over 280 days and 40 weeks). Since the total number of the cycles was 400 (40 cycles per mix and 5 specimens per mix), ten cycles were performed per week. After the corrosion period, the concrete surrounding each bar was carefully removed by cutting the tension ties into two parts by means of a bench saw (no water was used in order to prevent the chlorides to be washed away). Particular attention was paid to avoid any possible damage to the bars, that were extracted and examined. Bar corrosion was detected only at crack locations (without significant cravice corrosion). In the case of SFRC specimens, the fibres exhibited some corrosion as well, close to the cracks, along the outer surface of the specimen and inside the bulk matrix.

Test results

In order to obtain the overall response of corroded bars and to make comparisons with undamaged bars (B500B red curve in Figure 1a), the bars extracted from the tension ties were tested in uniaxial tension. In Figure. 1a, the load-strain curves are plotted for the bars of both RC or SFRC50 tension ties. Pitting corrosion provokes a rather limited strength reduction (6% in both RC and SFRC50) and a higher ductility reduction (26% in RC and 22% in SFRC50). As shown in Figure. 1b, the pitting depth exhibits a very high variability in both RC and SFRC50, and there is no relationship between the pitting depth and the crack width (the latter ranging from 0.06 to 0.24 mm).

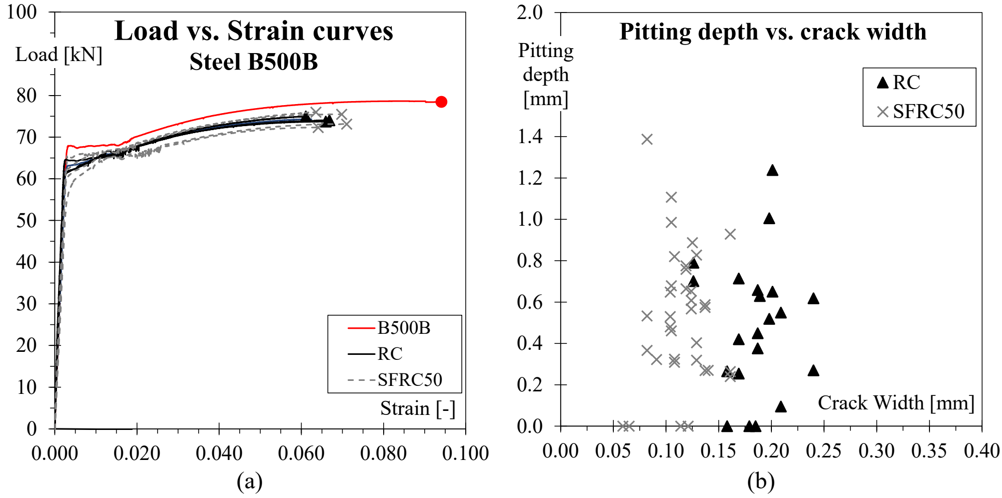

Figure. 1. Experimental response of the corroded bars in RC and SFRC50 tension ties (a,) and pitting depth vs. crack width at crack locations (b).

The mass loss and the pitting depth and volume, as well as the length of the corrosion spots along the rebars were evaluated. The average mass loss was -0.27% (2.1 grams/771.1 grams) and -0.26% (2.0 grams/771.4 grams) in RC and SFRC50 specimens, respectively. Since the mass-loss rates in the tension ties were 85 g/m^{2}y in RC and 81 g/m^{2}y in SFRC50, the two sets of tension ties behaved in a very similar way.

Concluding remarks

The test set-up adopted in this research project increases the acceleration of corrosion without using electric current. The rebars extracted from RC and SFRC50 tension ties after the wet-and-dry cycles show a similar response in tension, but in the latter ties the ductility is less affected. As for the propagation of corrosion in service conditions, fibres have a positive influence at least in the rather short periods of exposure adopted in this study.

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Original title of the thesis: *Design Aspects and Chloride-Induced Corrosion Behaviour of Fibre-Reinforced Concrete Structures*

Supervisors: *Professor Giovanni Plizzari and Dr. Antonio Conforti*

A FRAMEWORK FOR AUTOMATIC DAMAGE DETECTION IN STRUCTURAL HEALTH-MONITORING: INTERNET-CONNECTED PC BRIDGES AND BIG-DATA COMPUTER PROCESSING

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Keywords: structural-health monitoring, damage detection, prestressed-concrete bridges, prestress loss, multi-level approach, Internet of Things – IoT, Operational Modal Analysis – OMA, big-data analytics.

Introduction

Civil infrastructure facilities, such as bridges and tunnels, are generally affected by aging and degradation processes, with a loss in terms of expected performance. In the past two decades, Structural Health Monitoring (SHM) has assumed a key role in the management of civil infrastructures, as a means to have relevant information on the behaviour of critical systems. Nowadays, several techniques are available to recognize possible damage in civil engineering structures. Indeed, many damage identification methods have been developed over the years, either simple or sophisticated, capable of identifying even very small variations in the structural behaviour. In most cases, however, these techniques have been applied only to numerically-created cases or to small structures, and never to large structures monitored with many sensors.

In this research project, a robust methodology is presented ready to be effectively used in the continuous and automatic monitoring of a large number of structures instrumented with many sensors. One of the contributions is to try to fill up the huge difference existing between what has been developed over the years from a theoretical point of view and its applicability in the real world.

Proposed Methodology

A multilevel monitoring methodology has been developed, which does not need any by-hand configuration and is able to automatically set proper threshold values with the aim of effectively detect structural damage. In order to make the monitoring system - and therefore the damage-identification algorithms - reliable, efficient and robust, modal parameters are combined with statistical analysis and machine-learning approaches. The proposed methodology includes:

1. Development, implementation and testing of data acquisition and storage procedures, to efficiently collect sensors data, discarding those deemed to be lacking in information. This topic includes:
   a. development of a Principal Component Analysis (PCA) procedure for recognizing significant datasets;

   b. definition of a proper (minimum) time-window of continuous and synchronized data to be used in the accurate assessment of modal parameters;
   c. implementation of a statistical procedure to identify the observations characterized by scanty data (earthquakes, landslides, explosions);
   d. conception of spatial logics among sensor nodes, to create a communication network among neighbouring devices.
2. Development of a strategy to efficiently elaborate a large amount of data (big data) in the shortest possible time, fully exploiting the resources of the cloud platform.
3. Conception and development of a multilevel damage detection procedure, aimed at providing an early-stage alert concerning anomalous conditions. The "multilevel" attribute indicates that various methods, having different approaches, reliability and robustness in detecting the damage, have been integrated into a diagnostic framework based on different levels of alarm (three levels):
   a. First level, checked in each sensor node and based on statistical analysis.
   b. Second level based on a machine-learning model within the IoT gateway.
   c. Third level checked by the IoT cloud and based on OMA methods, used for verifying whether the anomaly condition is actually a structural damage or not.

   These three interrelated alert levels are able to take into account the spatial distribution of sensor network.
4. Implementation of a new parametric methodology to perform the automatic tuning of the parameters used for OMA identification algorithms.
5. Evaluation of the influence of the environmental factors on modal parameters and implementation of a procedure to automatically remove this influence from data.

The robustness, reliability and efficiency of the proposed methodology has been validated through numerical case-studies, before being applied to the long-term real-time monitoring of a significant number of structures (about 15 bridges) in operation.

Case Studies

The proposed monitoring methodology has been tested in two of the currently-monitored structures, both in northern Italy.

External tendons of a concrete highway bridge

In an internally - and externally - prestressed box-type highway bridge, vibration signals are acquired via a network of MEMS tri-axial accelerometers installed directly on the external prestressing tendons, aimed at predicting the maintenance needs ensuing from a gradual corrosion process activated by the incorrect mix design of the grout used to fill the ducts of the prestressing cables. Appropriate threshold values have been automatically generated by the system for each level of alarm, and the proposed framework has been activated for the long-term monitoring, with the following results:

1. The influence of environmental and operational variables on the modal parameters has been addressed and removed through a linear regression model, which have been automatically calibrated for each monitored tendon.
2. Real-damage scenarios have been detected by the system during the monitoring period. Three different events have been recorded:

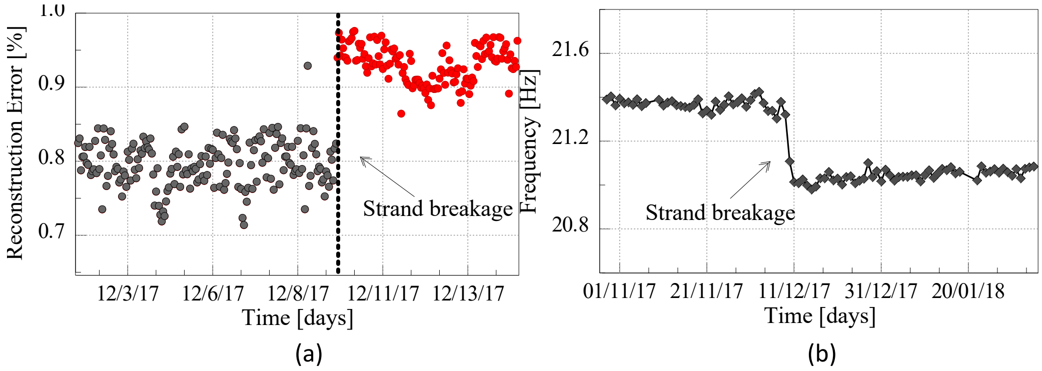

Figure 1. 2nd level alarm – machine learning (a); and 3rd level alarm – modal parameters (b).

a. The earthquake occurred in November 2017 caused the first level threshold to be exceeded by all the sensors of the structure, triggering more in-depth analysis (levels 2 and 3 were activated). However, neither level 2 nor level 3 were exceeded, indicating that no damage occurred in the structural members.
b. The possible breakage of a strand within one of the monitored cables caused the first level threshold to be exceeded by some sensors in December 2017. Thereafter, the second and third checks were automatically activated by the monitoring system and the analysis showed that one of the tendons exceeded both the second and third threshold levels (possible structural damage, Fig. 1).
c. The cable that suffered the damage in December 2017, was found broken in April 2018. Hence, the event recorded in December 2017 was actually related to the breaking of a tendon's strand, this being an unequivocal symptom of degradation.

Prestressed highway bridge

The bridge has been continuously monitored through a dynamic monitoring system since March 2019 (Fig.2). In May 2019, following the identification of widespread damage in one of the spans, strengthening works were carried out. Before strengthening the damaged span, triaxial accelerometers were installed in all the spans. The preliminary analyses carried out to have information on the dynamic behavior of the bridge soon after the installation of the monitoring system highlighted sizable differences between the damaged span and the remaining spans. The natural frequencies of the damaged span proved to be considerably lower than those of the undamaged spans, confirming the expected damage-induced stiffness-loss in the deck. At the same time, the vibration levels in the damaged span were significantly higher than in the undamaged spans.

The strengthening intervention carried out in May 2019 was entirely recorded by the sensors. During the strengthening works, the first level threshold was exceeded by all the sensors installed in the damaged span, due to the strong impulse recorded when the external tendons were tensioned. Following the first level alert, the second and third checks were automatically activated by the monitoring system, and - as a result of these deeper analyses - both the second and third threshold were exceeded by a group of sensors, indicating a possible structural damage.

Figure 2. Sensors installed on the bridge.

As a consequence, an alarm message, together with a phone call, was automatically generated and sent to the owner of the infrastructure.

In this case, the proposed methodology for the automatic and continuous identification of modal parameters proved to be quite effective in providing a very detailed characterization of the structural characteristics over long periods.

Concluding remarks

In the domain of continuous monitoring systems based on innovative methodologies instrumental in assessing the health state of existing structures, the proposed methodology allows to identify in real time any evolving damage in its initial stage and to generate - in case of anomalies - automatic alarms, which would activate management actions, possibly anticipating the disasters witnessed in recent years.

Outlook

Further work is needed to reduce the uncertainties on the modal parameters and to have information on the modal shapes. Last but not least, the physics of the given problem should be explicitly taken into account, to eliminate the effects that temperature has on natural frequencies.

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Original title of the thesis: *Structural Health Monitoring Framework for Automatic Damage Detection based on IoT and Big Data Analytics*

Supervisors: *Professors Gabriele Bertagnoli, Fabio di Trapani and Francesco Vaccarino*

Topic D

BEYOND THE STRUCTURAL BEHAVIOR

3D CONCRETE PRINTING: A NEW ERA IN CONSTRUCTION INDUSTRY

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Keywords: Additive manufacturing, concrete, 3D printing, compression tests, failure prediction

Introduction

The techniques of 3D printing - combined with appropriate cementitious materials - are successfully leading to the implementation of innovative manufacturing processes in the domain of cement-based products. Sizeable advantages are expected from the concrete technology based on layered extrusion (LE, see for instance [1]), that poses several engineering challenges, because large machines are required, as well as the formulation and characterization of innovative materials, the introduction of the reinforcement, surface finishing, formation of cold joints, etc. Moreover, printable materials should satisfy specific rheological requirements in order to achieve a balance between workability, extrudability and buildability (i.e., ability to stack concrete layers) [2].

In this perspective, the first step (pre-print phase) consists in optimizing concrete compatibility with the automated printing system. Unfortunately, the rheological properties of the cementitious materials suitable for 3D printing exhibit contradictory aspects. The absence of rigid moulds requires initial high strength and high stiffness, since - after concrete deposition at the fresh state - each layer must be able to carry itself and the weight of the layers above. Furthermore, mechanical properties change in time, and the longer the time intervals between subsequent layers, the greater the variability in terms of concrete strength and stiffness [3].

Experimental investigations are necessary to define the mechanical properties of the material, in order to optimize the printing process and to guarantee the stability of the printed item. The need to define a standard procedure is indisputable, as printability requires printable concretes to have faster curing rates than ordinary concrete. Hence, in order to test the material with reference to a specific printable curing time, tests must be carried out before hardening occurs [4].

Experimental program

The present work is focused on the evolution of both the strength and stiffness when the fresh mix turns from deformable to hardened. A printable cementitious composite is assumed as a "reference" (maximum aggregate size 4 mm) and its mechanical behavior (i.e., the compressive stress-strain law, the stiffness, the strength at yielding, …..) is investigated by testing cylinders in uniaxial unconfined compression (UUCTs), within the layer-cycle time (= time required to complete one single layer; range investigated in this study: 0-60 min after mixing). The mechanical parameters in the unlayered state (with the concrete cast in the traditional way) are the starting point for modelling the failure of the printed item. To this purpose, sensitivity analyses are carried out on various mechanical parameters in order to finalize standardised test methods for 3D printing. In particular:

- materials and specimen preparation: during an automated printing process, variations in the compaction/workability of the extruded material may occur due to a variety of reasons; furthermore, as the material is in the fresh state when it comes out of the printing nozzle, there are practical difficulties in numerically describing these conditions during the preparation of the specimen in the laboratory (i.e., pouring, compaction and demoulding);

- compressive test set-up: to run 3D printing properly, representative specimens must be subjected to compression; in fact, printable cement-based materials behave roughly like viscous-plastic Bingham materials [5], and their mechanical response is greatly affected by specimen size and by the loading rate; and

- in-time evolution of the stress-strain law in compression: early-age concrete compressive strength and stiffness inevitably evolve during the printing process at such a rate that each layer behaves differently.

The results of the uniaxial compressive tests are characterized by different test procedures, (a) to check the possible effect on the time-dependent mechanical properties of printable concretes, (b) to foresee possible failures during the printing process (because of self-buckling or excessive compression on the first/bottom layer), and (c) to shed light on how the maximum number of the layers may be affected by the technology adopted in the preparation of the specimens and by the displacement-controlled loading process (figure 1).

Test results

Tests in uniaxial unconfined compression were performed on the reference concrete-printable mix, in various conditions (differing for concrete age and preparation technology, as well as for test procedures) and the following conclusions can be drawn:

- concrete age affects early-age mechanical response; in fact, increasing the resting time to 60 min brings in a transition from a plastic to a brittle behavior, and increases both the strength and the stiffness, by roughly 5.5 and 3 times, respectively; changing test procedures has also a sizeable effect;

- varying the amount of the superplasticizer (SP) - as done in the reference mix - induces changes in material preparation/compaction; increasing and decreasing the quantity of the superplasticizer have sizeable effects on the strength and stiffness, as well as on the scatter of the test results; hence, an accurate reproduction of the physical state of the printing concrete is necessary, and both excessive compaction and rough pouring should be avoided;
- using – or not – nylon membranes (interposed between the cylindrical plastic mould and the outer surface of the specimen, to reduce interface adhesion during the casting process) shows that in the latter case (no membranes) the strength and stiffness are the lowest (for instance, 3.6-5.4 MPa and 62-124 kPa, respectively) with a very high statistical dispersion of the results; and
- for different concrete ages, the displacement rate of the loading process affects the stress-strain response; in fact, the higher the displacement rate, the higher the compressive strength (increments close to 50% were measured in the tests).

Figure 1. Maximum number of the layers: analytical prediction of the failure of the 3D-printed item, for each case under investigation.

Concluding remarks and outlook

Based on linear regressions applied to the test results (compressive strength and stiffness) obtained in each of the cases examined in this project, an analytical failure criterion was formulated to predict the two types of failure occurring in printed items (failure in compression and failure due to self-buckling). The effect of the test procedures on the prediction of the structural performance was investigated as well. The following conclusions can be drawn:

- in each test condition, the predicted failure is due to the loss of stability (= self-buckling);
- failure in compression is definitely more affected by the test procedures than failure due to self-buckling, especially when the variable parameter is the displacement rate of the loading process;
- using nylon membranes during the casting process improves the repeatability of the tests, making failure prediction more reliable; and
- changing test procedures markedly decreases the reliability of failure prediction.

Further efforts should be made to develop proper test guidelines concerning: concrete pumpability, replicability of extrusion conditions, thixotropic build-up time during the preparation of the specimens and more effective measurement techniques, to improve the calibration of the predictive models.

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Supervisor of the thesis: *Professor Ferdinando Auricchio*

FOAMED CONCRETE FOR 3-D PRINTING: PROPERTIES AND POTENTIAL OF AN INNOVATIVE BUILDING MATERIAL

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Keywords: foamed concrete, 3D concrete printing, lightweight concrete, thermal insulation, density, compressive and flexural strength, fiber-reinforced foamed concrete

Introduction

Foamed concrete belongs to the extended class of lightweight concretes and typically includes cement, water, preformed foam and fine sand [1]. The foam creates a system of air voids which give the material its peculiarities. In particular, low density brings in a reduction in structural size and is advantageous in the refurbishment or seismic retrofitting of seismically-vulnerable structures, as well as for thermal insulation, fire resistance, workability and cost-effectiveness (thanks to the use of quite simple easily-available constituents). A novel version of such a material is developed in this work, with the unique property of "extrudability" in a wide density range, meaning that the production process of a variety of structural and non-structural members can be carried out without formworks, based on an innovative 3D printing technology.

Experimental programme

Within this context and with reference to an innovative type of foamed concrete, the following properties are investigated in the density range spanning from 400 kg/m^3 to 800 kg/m^3: compressive and flexural strength with and without fibres according to UNI EN 196-1 and ASTM C-109) [2] [3], coefficient of thermal conductivity [4], and rheological and morphological properties. Comparisons are also made with ordinary foamed concrete [5].

Test results

The sizeable differences between ordinary and printable foamed concrete, in terms of fresh state properties, are highlighted in Figure 1. Printable foamed concrete is characterized by smaller and more homogeneously-distributed air bubbles than those commonly found in ordinary foamed concrete. Besides, thanks to a viscosity-enhancing agent, the higher confinement pressure required by the greater consistency of the fresh cementitious paste justifies a better microstructure, to the advantage of mix stability and to air-bubble retention inside the mix.

Figure 1. Differences at the fresh state between ordinary (a) and printable (b) foamed concrete.

These morphological differences contribute to the improvement of both the mechanical performance [6] and the thermal-insulation characteristics of printable foamed concrete compared to ordinary foamed concrete, and even to the much more energy-intensive autoclaved lightweight concrete [4].

Moreover, the addition of fibres improves the mechanical performance in bending, without compromising the low density, Figure 2.

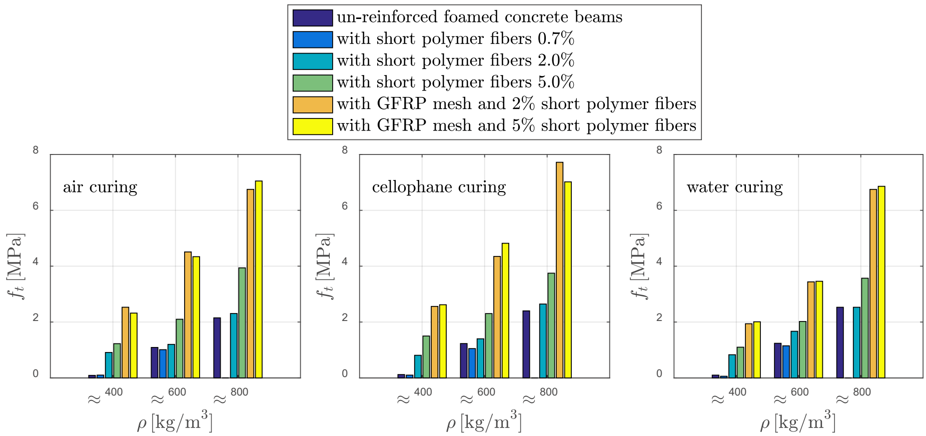

Figure 2. Light-weight foamed-concrete beams: histograms of the flexural strength for different reinforcement strategies and curing conditions, as a function of dry density.

Printability makes this new kind of foamed concrete suitable for simple, effective, efficient and innovative production processes, which require no formworks and exhibit a greater flexibility (with reference to both the structural/non-structural items to be produced and to the production processes as such). An interesting application is the in-situ production of multilayered insulating panels, Figura 3. The number of layers, as well as their density and thickness can be chosen according to the needs. Furthermore, thermal analyses confirm that the flexibility of the production process and the range of the items to be produced allows to obtain more effective solutions than those already on the market.

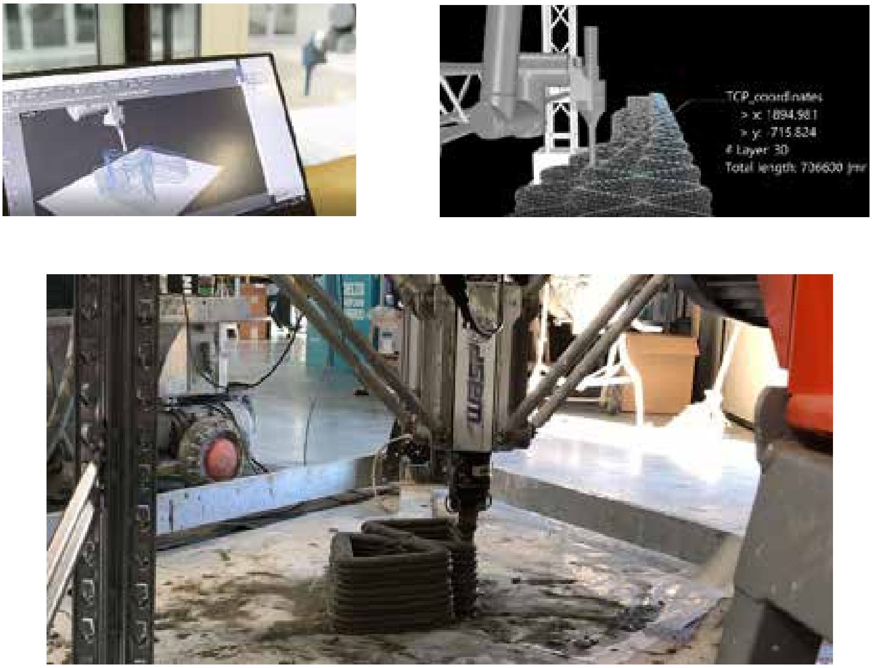

Figure 3. Design and 3D printing of lightweight foamed-concrete items.

Concluding remarks

Light-weight 3D-printable foamed concrete, unlike ordinary lightweight foamed concrete, can guarantee the shape of a given item at the fresh state without requiring any formwork, thanks to enhanced material's properties like cohesion and viscosity. Compared to ordinary foamed concrete, in 3D printable foamed concrete air bubbles are smaller and more homogeneously distributed within the cementitious paste thanks to the increased consistency at the fresh state. Consequently, 3D-printable light-weight foamed concrete has a higher compressive strength and a lower coefficient of thermal conductivity, for any given density.

3D-printable foamed concrete is suitable not only for the production in a prefabrication factory, but also for the direct in-situ automated production based on the use of robots. In this way, the building site turns into a smart factory for the production – as an example - of lightweight panels to be used as internal partitions, external walls and suspended ceilings. Finally, since introducing ordinary reinforcement is still an open issue in 3D concrete printing, the typical use of this technology is in the field of non-structural members or in that of fibre-reinforced structural members, provided that fibres be sufficient to guarantee the required bearing capacity.

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Supervisor of the thesis: *Professor Giuseppe Ricciardi*

COLD JOINTS IN 3D-PRINTED CONCRETE MEMBERS: AN EXPERIMENTAL AND NUMERICAL INVESTIGATION

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Keywords: 3D concrete printing; bond strength; shear strength: interlaminar reinforcement; failure modes; testing and modelling; dynamic response

Introduction

The interest and use of additive manufacturing (AM), also known as 3D printing, has grown dramatically at both the research and industrial level, becoming a revolutionary technology that may deeply affect design practice. In the construction sector, automation has recently made a breakthrough which is favouring the creation of significant synergies and the introduction of innovative automatized manufacturing techniques such as “digital fabrication” [1]. This approach involves the manufacture of items from a 3D digital model by adding material without formworks, starting from the conception of the item by means of Computer-Aided Design - CAD technology.

In this context, the technology of 3D Concrete Printing (3DCP) based on the automated layer-by-layer casting of cementitious materials, has progressed rapidly over the last years [2]. In spite of their high potential, many technological issues are still open to investigation, with specific reference to cementitious materials, such as the occurrence of weak surfaces at the bonded interface between contiguous printed filaments (cold joints). These weak surfaces depend mainly on the time elapsed between the printing of two consecutive layers, as the higher the waiting time, the lower the bonding among the layers [3].

Within this framework, a contribution to the assessment of the mechanical behaviour of layer-to-layer interfaces is provided by the present experimental/ numerical work, through the design of appropriate setups. A possible reinforcement system is proposed and tested as well, based on steel rods passing across the junctions to investigate the effect that such rods may have on the shear resistance of the joints. Attention is focused also on the assessment of interlock role in resisting dynamic loading.

Experimental and numerical program

The experimental campaign, carried out in Naples at the Laboratory of the Department of Structures for Engineering and Architecture of Naples, and in Lugano at the DynaMat

Laboratory of the University of Applied Sciences of Southern Switzerland (SUPSI), is presented. In the experimental program, mechanical tests are performed on printed and normally-cast prisms, but the technique based on digital-image correlation (DIC) is used as well, to investigate the strain distribution at different pre-failure stages and to have a visual support instrumental in defining failure mechanisms (Figure 1). The tests were performed in both quasi-static and dynamic conditions on specimens made of a cement-based mortar characterized by a low water-cement ratio (to enhance the buildability of the material) and by appropriate amounts of fibres and superplasticizer (to guarantee an adequate workability). The printer was produced by an Italian company.

The mechanical characterization in quasi-static conditions was devised to assess the shear behaviour of layered prisms by using a setup based on a modified version of the Punch-Through Sheat Test [4], while at medium and high strain-rates a Modified Hopkinson Bar and a Hydro-Pneumatic Machine were used [5][6]. The same experimental campaign was performed on printed RC specimens.

Last but not least, the experimental results were fitted via numerical modelling based on FEM (Finite Element Method).

Test results

The quasi-static tests were aimed at deriving the load-displacement curves and the crack patterns were monitored under increasing loads through Digital-Image Correlation, which shows that shear controls both cracking and failure modes. The tests shed light also on the roles of such different features as the waiting time (= time between the printing of two successive layers = 100, 200, 1800 and 3600s in this research project) and the strength of the interfaces. In this way, the correlation between the parameters of the printing process and interface behaviour can be quantified.

Numerical modelling has shown a satisfactory agreement between the theoretical and the experimental results.

The load-displacement curves and the evolution of the damage resulting from the tests carried out on printed reinforced prisms were correlated with – and validated through - numerical modelling, which shows a sizeable increase in shear strength with respect to the 3D prisms devoid of interlaminar reinforcement. In fact, the reinforcement enhances the shear strength thanks to a sort of dowel action, as in traditionally-reinforced concrete members.

The test results concerning traditionally-cast specimens show that the maximum loads are about 45% and 20% higher than those of printed unreinforced and reinforced specimens, respectively. Such a finding is a confirmation that cold joints (at the interface between two layers) are weak zones, regardless of the time gap between the deposition of two successive layers.

The results from the dynamic characterization of the specimens produced through the 3D-printing technique reveal that in dynamic conditions, the greater the waiting

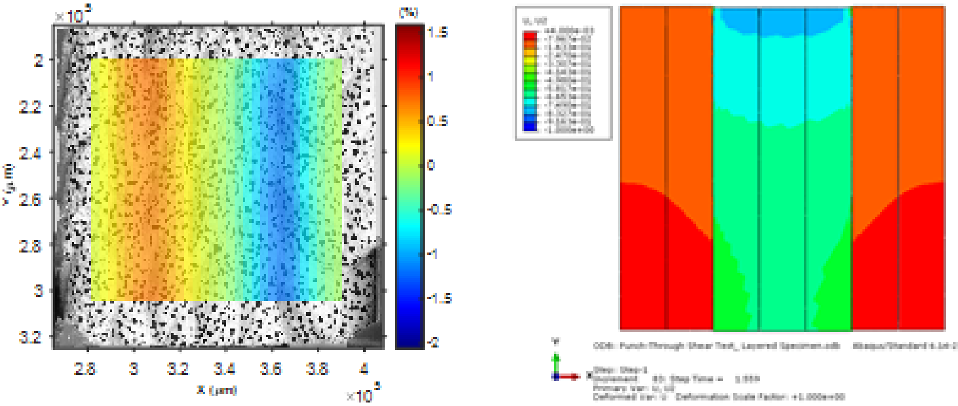

Figure 1. Unreinforced specimen at failure: (a) shear-strain distribution from DIC; and (b) vertical- displacement distribution from numerical modelling.

time, the less performing the layered material with reference to shear and tension.

On the whole, for increasing values of the waiting time the results exhibit a decrease in the interface dynamic strength in tension, from roughly -90% for medium strain-rates to roughly -20% for high strain-rates. In fact, both the maximum load and the tensile strength tend to decrease, because increasing the waiting time in printed specimens yields more microcracking in the weaker material.

Finally, concerning the shear behaviour of the specimens, the tests show that the longer the waiting time, the more brittle the failure mode.

Concluding remarks

An attempt to characterize the mechanical properties of the interfaces in 3D-printed concrete items - in both quasi static and dynamic loading conditions - is presented and discussed in this paper. An experimental setup is proposed to investigate the response of different printed specimens in terms of failure mechanisms and effectiveness of the bonding between contiguous layers.

The experimental setup has been designed and validated by means of numerical modelling in which the interfaces are assumed to be cohesive.

The very satisfactory fitting of the test results leads to the conclusion that the proposed FE model seems to be a reliable tool to investigate the many parameters affecting the success of 3D concrete printing.

A preliminary and fairly rough reinforcing system is proposed as well to overcome the weak interfaces in 3D-printed concrete items. The proposed system increases the shear strength of the printed specimens and can also modify the failure mode, to the advantage of ductility.

Outlook

The mechanical behaviour of interfaces in 3D concrete items is still an open issue, whose many aspects will be treated in the continuation of this research project.

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Original title oft he Thesis: *Experimental and Numerical Investigations on Cold Joints in 3D Concrete Printed Elements*.

Supervisor of the Thesis: *Professor Domenico Asprone*

WINNERS OF FEDERBETON – ACI ITALY CHAPTER's AWARDS 2020

VINCITORI DEI PREMI FEDERBETON – ACI ITALY CHAPTER 2020

Judgements of the Board of Examiners
Motivazioni della Commissione Giudicatrice

Denny Coffetti

La Tesi si caratterizza per l'ampiezza e l'attualità degli interessi tecnico-scientifici che spaziano dalla sperimentazione di materiali da costruzione innovativi – basati su leganti ad attivazione alcalina e su cementi sulfo-alluminati - e dall'esteso esame di molti risultati sperimentali, allo sviluppo di un nuovo indice di sostenibilità in grado di tener conto non solo dei parametri ambientali, ma anche degli aspetti relativi alla durabilità e alle prestazioni in senso lato dei materiali da costruzione, quali resistenza, modulo elastico, stabilità dimensionale ed isolamento termico. L'obiettivo finale rimane quello di realizzare materiali da costruzione comportanti ridotte emissioni di anidride carbonica in fase di produzione, e di poter effettivamente stabilire un indice di sostenibilità oggettivo per qualsiasi materiale da costruzione. Gli aspetti innovativi relativi allo sviluppo di due nuovi materiali da costruzioni sono ben messi in luce ed adeguatamente commentati, ed anche gli esempi applicativi sono non solo concettualmente importanti, ma anche di forte impatto ingegneristico e tecnologico. L'ampiezza e gli aspetti innovativi della tesi si accompagnano ad un'ottima organizzazione per ben definiti passi successivi e ad una elevata qualità editoriale.

Nataša Kalaba

Nell'ambito della Sicurezza Strutturale all'Incendio, la Tesi riguarda il tema di grande interesse della fase di decadimento degli incendi naturali, quando la diminuzione della temperatura ambientale è spesso accompagnata da ulteriore riscaldamento all'interno della struttura a causa della sua inerzia termica. Tuttavia, l'aggiornamento delle caratteristiche termiche e meccaniche di calcestruzzo ed acciaio d'armatura, durante la fase di decadimento dell'incendio, è un problema ancora aperto nella modellazione numerica degli elementi strutturali in c.a. esposti al fuoco come mostra questa Tesi, che affronta il tema a vari livelli di reversibilità del danno termico, con riferimento anche agli spostamenti del 2° ordine. Dei tre approcci adottati nell'analisi numerica non lineare di elementi strutturali particolarmente significativi ben documentati in letteratura - travi e colonne in c.a. - quello sezionale si dimostra il più conservativo, mentre quello basato su elementi finiti tridimensionali risulta essere molto realistico e di grande potenzialità, pur presentandosi piuttosto oneroso nei casi assai frequenti di elementi strutturali semplici. Per questi ultimi, gli elementi finiti tipo trave sono molto efficaci e di uso non troppo complesso. Lo studio fornisce risultati convincenti e significativi anche a fini normativi, e si presta ad interessanti estensioni.

Pietro Meriggi

La Tesi tratta del tema assai dibattuto della sostenibilità, compatibilità e rapporto costi-benefici dei sistemi di rinforzo strutturale costituiti da matrici cementizie ed idrauliche rinforzate con tessili, da applicare a costruzioni esistenti in calcestruzzo, muratura o blocchi lapidei, in alternativa (ed è l'aspetto innovativo) all'uso di matrici polimeriche. I due sistemi proposti – con rete di fibre basaltiche ovvero con microtrefoli di acciaio – vengono studiati in riferimento alle caratteristiche meccaniche ed al comportamento – anche su tavola vibrante - nel rivestimento di pannelli a tre strati (di cui i due esterni in muratura), in regime sia membranale che flessionale. In ambedue i casi le malte proposte sono risultate molto efficaci nel migliorare il comportamento strutturale. I dati sperimentali permettono di formulare equazioni progettuali per la valutazione della capacità resistente flessionale, mentre per il comportamento membranale viene proposta un'equazione ove il contributo del rivestimento in malta fibrorinforzata è di tipo additivo. Il duplice obiettivo - affinamento tecnologico delle malte cementizie armate con tessili inorganici, e progettazione strutturale – dà particolare valore alla Tesi, che rappresenta un contributo significativo nell'ambito del rinforzo e ripristino strutturale, molto importante a livello nazionale e di crescente interesse a livello internazionale.

HONORABLE MENTIONS

MENZIONI DI MERITO

FEDERBETON – ACI ITALY CHAPTER's AWARDS 2020

Alberto Belli

La Commissione ha particolarmente apprezzato nella tesi l'attenzione alla multifunzionalità dei compositi cementizi studiati, con uso di materiali di riciclo, grafene e polveri di carbonio.

Daniele Colonna

La Commissione ha valutato molto favorevolmente il contesto ecologico della tesi dedicata ai cementi sulfo-alluminosi usati in diversi rapporti con il cemento Portland, per ridurre le emissioni di anidride carbonica.

Clementina Del Prete

La Commissione ha riconosciuto nell'abbinamento fra sperimentazione e modellazione numerica il pregio della tesi, che studia ai vari livelli di scala i calcestruzzi rinforzati con macrofibre polipropileniche e poliviniliche.

Giuseppe Ferrara

La Commissione ha identificato nell'accoppiamento fra materiali "verdi" (malte cementizie contenenti fibre di lino), loro tecnologia di produzione e rafforzamento delle murature l'aspetto innovativo dei molti risultati della tesi.

Riccardo Nitiffi

La Commissione ha molto apprezzato l'aspetto strutturale della tesi dedicata alla modellazione dei nodi trave-colonna in c.a. con riferimento al taglio, al comportamento ciclico ed alla affidabilità della modellazione numerica.

Innovation in Concrete Structures and Cementitious Materials - 2020

Editors Luigi Coppola and Pietro G. Gambarova

The long summaries of the doctoral dissertations defended in Italy in 2019 and 2020 are presented in this volume with the focus on structural cementitious composites, reinforced-/prestressed-concrete construction and structural design. As in the previous volumes spanning the periods 2012-14, 2015-16 and 2017-18, 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 2019 e 2020 vengono presentati in questo volumetto con riferimento ai conglomerati cementizi strutturali, alle costruzioni in calcestruzzo armato e precompresso, ed alla progettazione. Come nei precedenti volumetti relativi a 2012-2014, 2015-2016 e 2017-2018, 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.

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