PRELIMINARY SCIENTIFIC PROGRAMME

– *fib* SYMPOSIUM 2015

Monday 18th-20th May, 2015

TOPICS:

- Analysis and Design
- Civil Works
- New Materials and Structures
- Life Cycle Design
- Modelling of Concrete
- Conservation of Structures
- Numerical Modeling
- Safety and Reliability
- Innovation in Buildings

MONDAY MORNING

Room: Carstensen

9.00-10.30 WELCOME

OPENING PERFORMANCE

WELCOME ADDRESS
by Kaare K. B. Dahl and Harald S. Müller, fib President

PRESENTATION OF *fib* MEDAL OF MERIT AND *fib* HONORARY MEMBERSHIP
by Harald S. Müller, fib president

PRESENTATION OF *fib* AAYE WINNERS
by Fernando Stucchi, AAYE Jury Chair

PROFESSORS B.J. RAMBØLL AND J.G. HANNEMANN IN MEMORIAM
by Mikael W. Bræstrup

10.30-11.00 BREAK

11.00-12.30
KEYNOTE SPEAKERS

Civil works
THE DEVELOPMENT OF THE CONCRETE REQUIREMENTS FEHMARNBELT FIXED LINK
Ulf Jönsson, Construction Manager, Femern A/S

New Materials and Structures
DIGITAL FABRICATION OF A FULL-SCALE SCULPTURAL CONCRETE STRUCTURE
Thomas Juul Andersen. Danish Technological Institute, Co-authors: Nyholm and Greisen

Life cycle design
THE ROLE OF LIMIT STATE SELECTION IN THE DESIGN AND MANAGEMENT OF SUSTAINABLE REINFORCED CONCRETE INFRASTRUCTURE
Michael D. Lepech, Stanford University

12.30-14.00 LUNCH

MONDAY AFTERNOON

Room: Carstensen

14.00-15.30
Young Engineer Award Session
OPENING REMARKS
by Fernando Stucchi, Jury Chair

WINNER OF RESEARCH CATEGORY:
JOÃO PEDRO SANTOS

WINNER OF RESEARCH CATEGORY:
YUGUANG YANG

WINNER OF DESIGN & CONSTRUCTION CATEGORY:
LUCA CARGNINO

SPECIAL MENTION, DESIGN AND CONSTRUCTION:
KÅRE FLINDT JØRGENSEN

CLOSING REMARKS
by Fernando Stucchi, Jury Chair

Room: Harlekin

14.00-15.30
TOPIC: CIVIL WORKS

Session: Civil works I
OPTIMIZED TBM TUNNEL SOLUTION FOR THE FEHMARNBELT FIXED LINK
by Pompeu-Santos

THE "DEURGANCKDOK LOCK" PORT OF ANTWERP
by Pauwels, De Kesel

SLIPFORMING OF HIGH STRENGTH CONCRETE
by Fosså

THE DESIGN AND CONSTRUCTION OF A STEEL-CONCRETE COMPOSITE RAILWAY VIADUCT
by Stroscio

THE "NEW EUROPA BRIDGE" CROSSES THE RIVER DANUBE
by Grange

DESIGN AND CONSTRUCTION OF THE MUKOGAWA BRIDGE
by Mizuno, Samizo, Fukuda, Kasuga

Room: Columbine

14.00-15.30
TOPIC: NEW MATERIALS AND STRUCTURES

Session: Structures I
ASSEMBLY AND LIFTING OF PEARL-CHAIN ARCHES
by Halding, Hertz, Viebæk, Kennedy

HOMOGENEITY AND STRENGTH OF MORTAR JOINTS IN PEARL-CHAIN BRIDGES
by Lund, Arvidsson, Kielsgaard Hansen

DURABLE EXPANSION JOINT FOR LONG INTEGRAL ABUTMENT BRIDGES
by Eichwalder, Kollegger, Kleiser

TECHNOLOGICAL DEVELOPMENT OF PC BRIDGE WITH HIGH DURABILITY TO SALT DAMAGE
by Toyofuko, Uezu, Kamiyama

APPLICATION OF ENGINEERED CEMENTITIOUS COMPOSITES TO PRECAST BEAM-COLUMN SUB-ASSEMBLAGE UNDER COLUMN REMOVAL SCENARIOS *by Kang, Tan*

EXPERIMENTAL AND ANALYTICAL STUDIES ON BEHAVIOR OF BRACKET STRUCTURES REINFORCED WITH CONCRETE ADHESIVE AND CFRP SHEET
by Yamashita, Hiroi, Arazoe, Yamamoto, Miyagawa

Room: Pjerrot

14.00-15.30
TOPIC: LIFE CYCLE DESIGN

Session: LCA, LCC and Service Life I
MAINLINE - MAINTENANCE, RENEWAL AND IMPROVEMENT OF RAIL TRANSPORT INFRASTRUCTURE TO REDUCE ECONOMIC AND ENVIRONMENTAL IMPACTS *by Linneberg, Solgaard, Jensen, Sloth*

SUSTAINABILITY AND DURABILITY GO HAND IN HAND, THE APPLICATION OF A COMBINED SUSTAINABILITY AND DURABILITY APPROACH TO A LARGE TUNNEL PROJECT IN ABU DHABI
by Jackson, Høibye, Edvardsen

HOW LIFE CYCLE COSTS CRITERIA MAY BE USED FOR DESIGN LIFE AND / OR REPLACEMENT CYCLE
by Solgaard, Edvardsen, Matos, McKenna

FIELD AND LABORATORY STUDIES ON THE SERVICE LIFE PREDICTION OF RC STRUCTURES IN MARINE ENVIRONMENT *by Safehian, Ramezanianpour*

EFFECT OF ENVIRONMENTAL FACTORS ON CHLORIDE INGRESS INTO CONCRETE IN THE MARINE ATMOSPHERE ZONE OF WAKAYAMA PREFECTURE
by An, Mihoichi, Noguchi, Hata, Kaneshiro, Shirato

PERFORMANCE EVALUATION AND REMAINING LIFE PREDICTION OF AN EXISTING BRIDGE BY J-BMS *by Miyamoto, Emoto*

15.30-16.00 BREAK-POSTER

Room: Carstensen

16.00-17.30
TOPIC: ANALYSIS AND DESIGN

Lead Paper session
INVESTIGATION OF SHEAR DESIGN ACCORDING TO *fib* MODEL CODE 2010 AND UNDERLYING THEORIES *by Norskov, Strørup, Hagsten*

Session: Shear I
ON THE DEVELOPMENT OF A THEORY FOR FLEXURAL MEMBERS FAILED IN SHEAR
by Tung, Tue

SHEAR DESIGN OF REINFORCED AND PRESTRESSED CONCRETE BEAMS BASED ON A MECHANICAL MODEL *by Marí, Jesús Miguel, Cladera, Ribas*

ANALYTICAL INVESTIGATION ON SHEAR FAILURE MECHANISM OF RC T-BEAMS WITH STIRRUPS *by Nakamura, Sato*

THE SHEAR RATIO AND TYPE OF APPLIED LOAD - EXPERIMENTAL ANALYSIS FOR THE CRITICAL CROSS-SECTION *by Bodzak*

Room: Harlekin

16.00-17.30
Session: Civil works II
ENHANCING PERFORMANCE & APPEARANCE OF OPEN SPANDREL ARCH BRIDGES
by Panday

THE DESIGN AND CONSTRUCTION OF PRECAST CONCRETE COMPONENTS FOR BRIDGES ALONG A ROAD WIDENING SCHEME
by Stroscio

INTEGRAL BRIDGES: RECENT TREND TO ENHANCE BRIDGE FEATURES *by Panday*

BUILDING BRIDGES USING LIGHTWEIGHT BRIDGE GIRDERS OUT OF CONCRETE
by Foremniak, Kollegger, Eder

STUDY ON 500M SPAN EXTRADOSED BRIDGES *by Kasuga*

DESIGN AND CONSTRUCTION OF OKEGAWA VIADUCT WHICH HAS PRECAST SEGMENTAL U-SHAPED BUTTERFLY WEB GIRDERS
by Kasuga, Homma

SAFE DEMOLITION AT TAMPA INTERNATIONAL AIRPORT *by Konz*

RECEPTION

Room: Columbine

16.00-17.30
Session: Structures II
DESIGN OF A CONCRETE ELEMENT DOME FOR ROSKILDE FESTIVAL
by Ludwigsen

ULTRA-LIGHT CONCRETE MEMBERS INSPIRED BY BAMBOO
by Busse, Empelmann

EFFECT OF FRP REINFORCEMENT ON ARCHING ACTION IN FRP-STRENGTHENED CONTINUOUS CONCRETE BEAMS
by Zeng, Caspeele, Taerwe

ON THE CONCEPTION OF FLOATING CONCRETE STRUCTURES
by Chyra, Arana Villafán, Sigrist

CRACK INHIBITING FOR UNDERGROUND SIDEWALL STRUCTURE BASED ON DUAL-REGULATION TECHNOLOGY OF TEMPERATURE FIELD AND EXPANSION HISTORY
by Tian, Wang, Zhang, Liu, Miao

CABLE-STAYED FOOTBRIDGE WITH UHPC DECK OVER THE LABE RIVER IN CELAKOVICE
by Kalny, Komanec, Kvasnicka, Broz, Koukolik, Vitek

Room: Pjerrot

16.00-17.30
Session: LCA, LCC and Service Life II
SELECTIVE USE OF STAINLESS STEEL REBAR TO INCREASE CONCRETE DURABILITY *by Borderon*

THE NEW COASTAL ROAD ON REUNION ISLAND (FRANCE): APPLICATION OF DURABILITY MODEL TO A REAL CASE *by Mai-Nhu, Rougeau, Linger, Denis, Magne*

EFFECT OF CORROSION ON THE FATIGUE SERVICE-LIFE OF REINFORCED CONCRETE BEAMS
by Veerman

MULTI-PHYSICS AND MULTI-SCALE DETERIORATION MODELLING OF REINFORCED CONCRETE PART I: COUPLING TRANSPORT AND CORROSION AT THE MATERIAL SCALE *by Michel*

MULTI-PHYSICAL AND MULTI-SCALE DETERIORATION MODELLING OF REINFORCED CONCRETE PART II: COUPLING CORROSION AND DAMAGE AT THE STRUCTURAL SCALE
by Lepech, Rao, Kiremidjian, Michek, Stang, Geiker

DURABILITY DESIGN OF THE LONGEST BRIDGE IN NEW YORK STATE *by Solgaard, Edvardsen, Langlois*

RECEPTION

TUESDAY MORNING

Room: Carstensen

9.00-10.30
TOPIC: ANALYSIS AND DESIGN

Session: Shear II

INVESTIGATIONS INTO THE SHEAR LOAD BEARING CAPACITY OF A PRESTRESSED TWO-SPAN CONCRETE BEAM - FINDINGS FROM A LARGE SCALE EXPERIMENT
by Gleich

SHEAR BEHAVIOR OF EXISTING BRIDGES WITHOUT AND WITH A MINIMUM AMOUNT OF SHEAR REINFORCEMENT *by Huber*

EFFECT OF SHRINKAGE AND STRENGTH DEVELOPMENT HISTORIES ON HIGH STRENGTH CONCRETE BEAMS IN SHEAR
by Matsumoto, Osakabe, Niwa

DEFORMABILITY OF REINFORCED CONCRETE MEMBERS IN SHEAR *by Hong*

TEST AND ANALYSIS OF PARTLY PRECAST RC SHEAR WALL *by Li, Lu, Xilin*

SEISMIC BEHAVIOUR OF REINFORCED CONCRETE WALLS WITH MINIMUM VERTICAL REINFORCEMENT *by Lu, Henry*

Room: Harlekin

9.00-10.30
TOPIC: MODELLING OF CONCRETE

Lead Paper Session

AN INNOVATIVE EXPERIMENTAL PROCEDURE TO ENHANCE UNDERSTANDING OF REBAR-CONCRETE BOND
by Dancygier, Leibovitch, Yankelevsky

Session: Mechanics

A PROBABILISTIC MODEL TO PREDICT AGGREGATES SIZE DISTRIBUTION EFFECT ON THE COMPRESSIVE STRENGTH OF NORMAL AND HIGH STRENGTH CONCRETES
by Miled, Limam, Sab

EVALUATION OF MECHANICAL PROPERTIES OF CONCRETE
by Munch-Petersen, Meson

CONSTITUTIVE MODEL FOR SHEAR TRANSFER IN ULTRA HIGH PERFORMANCE FIBER REINFORCED CONCRETE
by Lee, Hong

INFLUENCE OF TEMPERATURE ON THE FATIGUE BEHAVIOUR OF CONCRETE
by Elsmeier

Room: Columbine

9.00-10.30
TOPIC: NEW MATERIALS AND STRUCTURES

Session: Structures and UHPC

PREFABRICATED NON-STANDARD SHELL STRUCTURES MADE OF UHPC – STRUCTURAL CONNECTIONS
by Santner, Freytag, Trummer

SHAPE OPTIMIZED STRUTS MADE OF ULTRA-HIGH PERFORMANCE CONCRETE
by Henke, Fischer

EFFECT OF U-SHAPED WIRE MESHED UHPCC PERMANENT FORMON THE FLEXURAL-BEHAVIOURS OF RC BEAM *by Wu, Lin*

FULL UHPFRC C200 PEDESTRIAN BRIDGE IN EINDHOVEN, THE NETHERLANDS
by Tirimanna, Falbr

STRESS REDISTRIBUTION IN BRIDGES BUILT WITH ULTRA-THIN PRECAST GIRDERS
by Suza, Kollegger

PRESTRESSED I-BEAMS MADE OF ULTRA-HIGH PERFORMANCE CONCRETE FOR CONSTRUCTION OF RAILWAY BRIDGES
by Tej, Kolísko, Bouška, Vokác, Cech

Room: Pjerrot

9.00-10.30
TOPIC: LIFE CYCLE DESIGN

Session: LCA, LCC and Service Life III

A SUSTAINABILITY COMPARISON BETWEEN RENOVATION AND NEW BUILD OPTION FOR THE GALECOPPER BRIDGE *by Villa, Den Blanken, Thie*

PRECAST CONCRETE FOR SUSTAINABLE BUILDINGS *by Nieminen*

TOPIC: CONSERVATION OF STRUCTURES

Lead Paper session

SETTING UP OF A DATABASE DEDICATED TO DURABILITY INDICATORS BY THE CIVIL WORKS FRENCH ASSOCIATION (AFGC) TO SUPPORT THE IMPLEMENTATION OF CONCRETE PERFORMANCE-BASED APPROACH
by Linger, Carcasses, Cussigh, Rougeau, Barberon, Thauvin, Cassagnbere, Mai-Nhu, Dierkens

Session: Asset Management

MANAGEMENT OF M4 ELEVATED SECTION SUBSTRUCTURES
by Brock, Hendy, Nicholls

10.30-11.00 BREAK

10.30-11.00 BREAK

Room: Carstensen

11.00-12.30
Session: Shear III

EXPERIMENTAL INVESTIGATIONS ON THE SHEAR CAPACITY OF RC SLABS UNDER CONCENTRATED LOADS – INFLUENCE OF DEGREE OF RESTRAINT AND MOMENT-SHEAR RATIO
by Reissen, Hegger

LIMIT ANALYSIS FOR PUNCHING SHEAR DESIGN OF COMPACT SLABS AND FOOTINGS
by Fernández Ruiz, Simões, Muttoni, Viúla Faria

MODIFIED BOND MODEL FOR SHEAR IN SLABS UNDER CONCENTRATED LOADS
by Lantsoght, Van der Veen, De Boer

PUNCHING OF RC THICK PLATES – EXPERIMENTAL TESTS AND ANALYSIS
by Krakowski, Swiniarski, Urban

PUNCHING IN POST-TENSIONED CONCRETE FLAT SLABS WITH EDGE COLUMNS
by Melo, Barban

FLAT SLAB PUNCHING BEHAVIOUR UNDER CYCLIC HORIZONTAL LOADING
by Almeida, Inácio, Lúcio, Ramos

Room: Harlekin

11.00-12.30
Session: Cracking and Transport I

FATIGUE BEHAVIOUR OF HIGH-STRENGTH GROUTING CONCRETE TESTED UNDER WATER
by Hümme

ON THE CRACKING LOCALIZATION IN TENSILE REINFORCED CONCRETE BARS WITH STEEL FIBERS
by Dancygier, Karinski

NUMERICAL 3D MODELLING OF ANCHORAGE, CORROSION AND SPALLING
by Kamyab, Lundgren

A RAPID AND REPEATABLE METHOD FOR ESTABLISHING THE WATER PERMEABILITY OF CRACKED MORTAR SPECIMENS
by Palin, Jonkers, Wiktor

LOCALIZATION OF ACOUSTIC EMISSION IN REINFORCED CONCRETE USING A HETEROGENEOUS VELOCITY MODEL AND MULTILINEAR WAVE PROPAGATION PATHS *by Gollob, Vogel*

CEMHAPP - AN APPLICATION FOR HYDRATION KINETICS COU-PLED WITH MULTISCALE FEM ANALYSIS *by Leal da Silva, Šmilauer*

Room: Columbine

11.00-12.30
Session: Materials I

DESIGN OF CONCRETE FOR HIGH FLOWABILITY: PROGRESS REPORT OF *fib* TASK GROUP 4.3
by Schmidt, Grünewald, Ferrara, Dehn

TIME- AND LOAD-DEPENDENT BEHAVIOUR OF FLOWABLE CONCRETE: PROGRESS REPORT OF *fib* TASK GROUP 4.3
by Leemann, Hammer, Grunewald, Ferrara, Dehn

IMPACT OF MOLECULAR STRUCTURE OF COMB-LIKE POLYMER ON DISPERSION PROPERTIES OF CEMENT PASTES
by Qiao, Ran, Liu

THE COLOUR POTENTIALS OF SSA-CONTAINING MORTAR
by Kappel, Bache, Ottosen, Kirkelund, Goltermann

COLOURED FAIR-FACED CONCRETE - EVALUATION OF COLOUR TONE
by Cauberg

Room: Pjerrot

11.00-12.30
Session: Asset Management and Diagnosis

BRIDGE MAINTENANCE MODELS USING EXPERT OPINION
by Guimarães, Campos e Matos

LONG TERM ASSET MANAGEMENT APPROACH FOR CONCRETE BRIDGES AND TUNNELS
by Knudsen, Andersen, Nielsen

EXPERT CENTRE FOR INFRASTRUCTURE MATERIALS
by Poulsen, Stang, Sørensen, Pade, Mathiesen

STUDY ON DIAGNOSIS METHOD FOR CABLE-STAYED AND EXTRADOSED BRIDGE WITH CONCRETE-STEEL COMPOSITE MAIN GIRDER
by Sakai

SEISMIC PERFORMANCE OF RC BEAMS FROM EXISTING BUILDINGS
by Araki, Hibino

DAMAGE ASSESSMENT OF A RC STRUCTURE AFFECTED BY FROST AND SALT ACTIONS
by Mizuta, Yoshinori, Hisatoshi, Norihiro, Akinori, Tetsuji

12.30-14.00 LUNCH

12.30-14.00 LUNCH

TUESDAY AFTERNOON

Room: Carstensen

14.00-15.30
TOPIC: ANALYSIS AND DESIGN

Session: Shear IV
EXPERIMENTAL INVESTIGATIONS OF PUNCHING SHEAR CONCRETE SLABS WITH DIFFERENT TYPES TRANSVERSE REINFORCEMENT
by Krawczyk, Urban

PUNCHING SHEAR STRENGTHENING OF FLAT SLABS: CFRP AND SHEAR REINFORCEMENT
by Moreno

LOAD CARRYING CAPACITY OF KEYED JOINTS REINFORCED WITH HIGH STRENGTH WIRE ROPE LOOPS
by Joergensen, Hoang

ONE-WAY SHEAR BEHAVIOUR OF INDIRECTLY LOADED LARGE FOOTINGS *by Uzel, Bentz, Collins*

ON THE RESISTANCE OF FASTENING PLATES WITH SUPPLEMENTARY REINFORCEMENT
by Bujňak, Farbak, Bahleda, Leinonen

THE INCREASING BEARING CAPACITY WHILE REMOVING CONCRETE FROM REINFORCED BEAMS
by Hoogen, Vergoossen, Blom

Room: Harlekin

14.00-15.30
TOPIC: MODELLING OF CONCRETE

Session: Cracking and Transport II
MOCK-UP FOR VERIFICATION OF TEMPERATURES IN LARGE CONCRETE STRUCTURES
by Aarre, Frederiksen

INVESTIGATION OF CRACK DEVELOPMENT IN A FAIRFACED CONCRETE FLOOR
by Waldmann, Weiler

CHLORIDE TRANSPORT IN CONCRETE STRUCTURAL ELEMENTS AFTER REPAIR
by Rahimi

NEW INSIGHTS FOR MODELING CHLORIDE INGRESS UNDER FREEZE-THAW LOADING
by Ferreira, Leivo

AN INVESTIGATION OF THE INFLUENCE OF VARYING EXPOSURE TEMPERATURE ON CHLORIDE INGRESS IN CONCRETE
by Poulsen, Sørensen

Room: Columbine

14.00-15.30
TOPIC: NEW MATERIALS AND STRUCTURES

Session: Materials II
SELF-HEALING CAPABILITY OF CONCRETE CONTAINING CRYSTALLINE ADMIXTURES IN DIFFERENT EXPOSURE CONDITIONS
by Roig-Flores, Moscato, Serna Ros, Ferrara

NANOTECHOLOGIES IN NEW STRUCTURAL CONCRETES: PRACTICE AND OUTLOOK
by Falikman, Gusev

CEMENTITIOUS HYBRID MATERIALS AND INTEGRATED TECHNOLOGY
by Greisen

CHALLENGE OF TEXTILE REINFORCED HIGH PERFORMANCE CONCRETE FOR SUSTAINABLE CONSTRUCTION
by Hajek, Novotna, Chira, Fiala, Vlach, Leiblova

CRC® – NEW CHALLENGES FOR NEW MARKETS USING ULTRA HIGH PERFORMANCE FIBRE REINFORCED CONCRETE
by Aarup, Hansen

EXPERIMENTAL BOND BEHAVIOR OF DEFORMED CFRP REBARS IN HIGH STRENGTH CONCRETE *by Akbas, Celik, Yalcin*

Room: Pjerrot

14.00-15.30
TOPIC: CONSERVATION OF STRUCTURES

Session: Diagnosis, Monitoring and Repair
DIAGNOSIS OF SEVERE ALKALI AGGREGATE REACTION IN A FINNISH SWIMMING POOL
by Holt, Lindqvist, Orantie, Ferreira

INNOVATIVE FIBER OPTIC MONITORING OF WADI LEBAN BRIDGE (KSA)
by Lebon, Paris, Lamour

REPAIR MONITORING OF CRACKED CONCRETE FLOOR USING THE IMPULSE – RESPONSE METHOD
by Zoidis, Tatsis, Vlachopoulos, Gotzamanis, Stærke Clausen, Aggelis, Matikas

APPLICABILITY OF CATHODIC PROTECTION BY GALVANIC ANODE SYSTEM FOR RC MEMBER UNDER COMBINED DETERIORATION OF CARBONATION AND MIXED CHLORIDES
by Yoshida, Otani. Takaya,, Yamamoto, Miyagawa

15.30-16.00 BREAK-POSTER

15.30-16.00 BREAK-POSTER

Room: Carstensen

16.00-17.30
Session: Columns and Elements I
LOAD CARRYING CAPACITY OF REINFORCED CONCRETE COLUMNS IN THE CONNECTION ZONE WITH SLAB OF LOWER STRENGTH CONCRETE
by Gołdyn

A CONFINEMENT MODEL FOR REINFORCED CONCRETE COLUMNS *by Tung, Tue*

EXPERIMENTAL STUDY ON 2-D RC FRAME WITH MIDDLE COLUMN REMOVED UNDER PROGRESSIVE COLLAPSE
by Lim, Lee, Tan

FORCE INTRODUCTION INTO FLANGES OF STRUCTURAL CONCRETE T-BEAMS
by Schütte, Sigrist

EFFECT OF THE INACCURACY ON THE STRESS DISTRIBUTION IN DRY CONNECTIONS OF MODULAR CONSTRUCTIONS
by Theiler, Reicht

Room: Harlekin

16.00-17.30
TOPIC: ANALYSIS AND DESIGN

Session: Fibre Reinforced Concrete
NEW SWEDISH DESIGN GUIDE FOR FIBRE CONCRETE STRUCTURES *by Silfwerbrand, Hedebratt*

CRACK WIDTHS IN CONCRETE WITH FIBERS AND MAIN REINFORCEMENT
by Christensen, Ulfkjær

SHEAR CAPACITY OF FIBER-REINFORCED CONCRETE *by Toubia, Ishtewi*

INFLUENCE OF STEEL FIBERS AND STIRRUPS ON THE STEEL-CONCRETE BOND BEHAVIOR
by El Debs, Correa

COMPRESSIVE FATIGUE STRENGTH OF SFC UNDER LOW-CYCLE FATIGUE LOAD *by Yoon*

ANALYTICAL MODELS FOR STRUCTURAL BEHAVIOUR OF FIBRE REINFORCED CONCRETE BEAMS WITH STEEL OR FRP BARS
by Ali, Sheikh, Oehlers

Room: Columbine

16.00-17.30
Session: Materials III
PROPERTIES OF PERVIOUS CONCRETE CONTAINING GROUND GRANULATED BLAST FURNACE SLAG (GGBFS) AS A SUPPLEMENTARY CEMENTING MATERIAL
by Joshaghani, Ramezanianpour

DESIGN AND PROPERTIES OF SUSTAINABLE CONCRETE
by Haist, Moffatt, Breiner, Müller

RECENT DEVELOPMENT OF ULTRA-HIGH STRENGTH PRESTRESSING 19-WIRE STRAND 29.0 MM
by Oshima

DELAYED CONCRETE PRESTRESSING WITH SHAPE MEMORY POLYMER TENDONS
by Pilegis, Teall, Hazelwood, Jefferson, Gardner, Lark

A NOVEL 2D VASCULAR NETWORK IN CEMENTITIOUS MATERIALS
by Davies, Jefferson, Gardner

Room: Pjerrot

16.00-17.30
Session: Repair
STUDY ON THE EFFECTIVE PROTECTION METHODS AGAINST CHLORIDE ATTACK IN SUBWAY TUNNELS
by Mutou

DEVELOPMENT OF REPAIR METHOD FOR CORRODED PC TENDONS IN INCOMPLETE GROUTING AREA USING LINO2-CONTAINING SOLUTION AND GROUT AND APPLICATION TO EXISTING PC BRIDGEs
by Kamotani, Aoyama, Morikawa

POST-INSTALLED REINFORCEMENT CONNECTIONS UNDER ULS, SLS AND SUSTAINED LOADS
by Kunz, Randl

REHABILITATION OF BALAD BRIDGE IN INDIA
by Panday

REHABILITATION OF A SEVEN STORIED BUILDING PROJECT: A UNIQUE CASE STUDY
by Panday

DINNER

DINNER

WEDNESDAY MORNING

Room: Carstensen

9.00-10.30
TOPIC: ANALYSIS AND DESIGN

Session: Columns and Elements II

CONCRETE ELEMENTS REINFORCED WITH LARGE DIAMETERS, PART 2: BOND BEHAVIOUR AND LAPPED JOINTS *by Schoening, Hegger*

CONCRETE ELEMENTS REINFORCED WITH LARGE DIAMETERS, PART 3: COLUMNS
by Oettel, Empelmann

BOND AND DEFORMATION BEHAVIOUR OF REINFORCED INFRA-LIGHTWEIGHT CONCRETE (ILC) *by Hückler, Schlaich*

DESIGN CONSIDERATIONS FOR SHEAR FAILURE OF FLAT CONCRETE SLABS EXPOSED TO FIRE
by Annerel, Taerwe

EFFECT OF IMPERFECTIONS ON CONCRETE COLUMNS SUBJECTED TO FIRE TAKING INTO ACCOUNT SECOND ORDER EFFECTS
by Wang, Caspeele, Taerwe

DESIGN FOR ACCELERATED HIGH STRENGTH CONCRETE CONSTRUCTION USING STRUT-AND-TIE MODEL
by Tantipidok, Stemberk

Room: Harlekin

9.00-10.30
TOPIC: NUMERICAL MODELLING

Lead Paper session
SHELLDESIGN – EFFICIENT AND INNOVATIVE DESIGN TOOL FOR CONCRETE STRUCTURES
by Nyhus

Session: Numerical Modelling I

PRELIMINARY ANALYSIS OF RC WALL ELONGATION
by Encina, Henry

DESIGN OF A MIXED FOUNDATION FOR THE HIGH SPEED RAILWAY STATION OF LODZ FABRYCZNA, POLAND
by Mugnier, Magne Tachago, Landi, Chiriotti

STEP-WISE NUMERICAL PROCEDURE FOR THE TIME-DEPENDENT MODELLING OF CONCRETE BEAMS TAKING INTO ACCOUNT CREEP AND CREEP RECOVERY
by Criel, Caspeele

SOLUTION STRATEGY FOR LARGE SCALE NON-LINEAR FINITE ELEMENT ANALYSES OF CONCRETE STRUCTURES
by Engen, Hendriks, Øverli, Åldstedt

Room: Columbine

9.00-10.30
TOPIC: NEW MATERIALS AND STRUCTURES

Session: Material Properties

CARBON REINFORCED CONCRETE UNDER CYCLIC TENSION LOADING *by Niederwald, Kauser*

COMPILATION AND STUDY OF A DATA BASE OF TESTS AND RESULTS ON FLEXURAL CREEP BEHAVIOR OF FIBRE REINFORCED CONCRETE SPECIMENS
by Llano-Torre, Garcia-Taengua, Martí Vargas, Serna Ros

SELF-COMPACTABILITY AND STRENGTH CRITERIA FOR CONCRETE MIXES WITH MINERAL ADDITIONS AND FIBRES
by Garcia-Taengua, Sonebi, Crossett, Taylor, Deegan

INFLUENCE OF CONCRETE FLOW ON SPATIAL DISTRIBUTION AND ORIENTATION OF FIBRES IN STEEL FIBRE REINFORCED SELF-COMPACTING CONCRETE
by Andries, Van Itterbeeck, Van Gysel, Vandewalle, Cauberg

BOND OF REBARS TO STEEL FIBER REINFORCED CONCRETE: MINIMUM CONCRETE COVER REQUIREMENTS TO PREVENT SPLITTING
by Garcia-Taengua, Mart-Vargas, Serna Ros

INFLUENCE OF TEMPERATURE BELOW 100 °C ON THE MECHANICAL PROPERTIES OF CONCRETE
by Accosta, Haist, Müller

Room: Pjerrot

9.00-10.30
TOPIC: CONSERVATION OF STRUCTURES

Session: Repair and Strengthening

FIRST BUILDING RETROFITTED TO EN-EUROCODE 8 TESTED BY DESIGN-LEVEL EARTHQUAKE
by Fardis, Liosatou, Kosmopoulos

STRENGTHENING THE CONCRETE COLUMNS WITH THE CARBON POLYMER FIBRES AND BEHAVIOUR UNDER CENTRIC LOADS *by Kabashi, Krasniqi, Nushi*

PERFORMANCE OF CONCRETE PANELS STRENGTHENED USING CFRP MATERIALS
by Kim, Jirsa, Ghannoum

STRENGTHENING OF M8-A8 BISHOPTON OVERBRIDGE
by McKenna, Dunne

FLEXURAL STRENGTHENING OF RC SLABS WITH PRETENSIONED AND NONPRETENSIONED NEAR SURFACE MOUNTED CFRP STRIPS
by Przygocka, Lasek, Kotynia

10.30-11.00 BREAK

Room: Carstensen

11.00-12.30
Session: Special Loadings and Conditions I

EVOLUTION OF DEFLECTIONS OF HAUNCHED BEAMS UNDER CYCLIC LOADS
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CHLORIDE-INDUCED DELAYED FRACTURE OF PRESTRESSING WIRES AND STRUCTURAL RELIABILITY OF PC BRIDGES *by Mino, Morikawa*

SPATIAL VARIABILITY OF MATERIAL PROPERTIES AND ITS INFLUENCE ON STRUCTURAL RELIABILITY OF UHPFC COLUMNS *by Tran, Grziwa, Graubner*

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by Mihaylov

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by Christian Munch-Petersen

PRESENTATION OF *fib* SYMPOSIUM IN CAPE TOWN. SOUTH AFRICA
by Harald S. Müller, fib President

PRESENTATION OF 2017 *fib* SYMPOSIUM IN MAASTRICHT, NETHERLANDS
by Dick A. Hordijk, Delegate

PRESENTATION OF 20188 *fib* CONGRESS IN MELBOURNE, AUSTRALIA
by Stephen Foster, Delegate

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15.30-16.00 BREAK-POSTER

16.00-17.30
CLOSING LECTURE AND CLOSING OF SYMPOSIUM

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INNOVATION IN BUILDINGS

PUNCHING SHEAR STRENGTHENING OF FLAT SLABS: CFRP AND SHEAR REINFORCEMENT

Carlos Moreno, Débora Ferreira, Abdelkrim Bennani, Ana Sarmento, and Michel Noverraz

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Abstract

Punching in slabs is usually associated to the application of concentrated loads or to the presence of columns. One of the main concerns related to flat slabs is its punching shear capacity at slab-column connection, which is subjected to a very complex three-dimensional stress state. Provided that bending capacity is installed, punching shear failure is hence characterized by the development of a truncated cone shaped surface at the slab-column connection. The experimental programme carried out by the authors includes four normal strength concrete slabs (1100×1100×100 mm^3), with and without shear reinforcement, submitted to punching under a concentrated load. One of the specimens included typical bent-down bars as shear reinforcement. Frequently, there is the need to strengthen existing flat slabs against punching shear failure. Current paper intends to further investigate the structural response of such reinforcement techniques. One of the strengthening practices, which have been tested within current experimental programme, consists on gluing carbon fibre reinforced polymers on concrete surface. Moreover, the near surface mounted technique has also been tested within current experimental work. Finally, a fourth specimen served as reference. The effects of shear reinforcement and of the carbon fibre reinforced polymers enhancing punching shear capacity are observed.

Keywords: Punching shear, CFRP, NSM, Building codes, Experimental tests

1 Introduction

One of the main concerns related to two-way flat slabs is the punching shear capacity at slab-column connection, which is subjected to a very complex three-dimensional stress state. Punching shear failure is hence characterized by the development of a truncated cone shaped surface at the slab-column connection. Punching shear can thus result from a concentrated load or reaction acting on a relatively small area, called the loaded area, of a slab or a foundation. This type of failure is usually both brittle and catastrophic since it may generate the global collapse of the structure due to the increasing load transfer to neighbouring columns and to the slabs located underneath. The load carrying capacity of reinforced concrete (RC) slabs may be compromised for a number of reasons, including structural damage, design errors, building code changes and alteration of functional use.

Two strengthening techniques enhancing directly the bending capacity of slab-column connections are employed. The collateral increase in the ultimate punching shear capacity is analysed. The use of carbon fibre reinforced polymers (CFRP) on structural repair and strengthening has continuously increased during the last years due to the following main advantages of this composite material when compared to conventional materials like steel and concrete: low specific weight, easy installation, high durability and tensile strength, electromagnetic permeability, and practically unlimited availability regarding size, geometry and dimensions (ACI 2008). The most widely used technique aiming to increase load carrying capacity is to apply CFRP plates on the tension surface of the RC slab as externally bonded (EB) reinforcement. CFRP laminates and sheets are generally applied on the faces of the elements to be strengthened configuring which is commonly designated as the EB reinforcing technique. The research carried out up to now has revealed that this method cannot mobilize the full tensile strength of CFRP materials due to the occurrence of premature debonding phenomenon (Nigro, Ludovico & Bilotta 2008). Due to the fact that CFRP is often directly exposed to the weathering conditions the reinforcing performance of this technique should be accounted for. EB systems are also vulnerable regarding fire action and vandalism acts. Alternatively, the near surface mounted (NSM) technique, which consists of cut-in openings strengthened with CFRP materials, can be used. This technique was used is some practical applications (Barros & al. 2006) and several benefits were pointed out. In order to assess the efficacy of this strengthening system as regards structural elements failing in punching shear, flat slab specimens were tested. The carried out tests are described and the most significant outcomes are presented and analyzed. Experimental results are also compared with design code predictions regarding the punching shear strength.

2 Design code provisions

A review on design code provisions is conducted. The punching shear approaches of CEB-FIP MC 90 (CEB-FIP 1993) and EN 1992-1-1 (CEN 2004) which is based on the former – otherwise referred to as Eurocode 2 – are analysed below.

Both design codes adopt an approach involving critical sections where punching shear capacities are to be checked as represented in Fig. 1: at the face of the column, at the basic control section, and at the outermost control section where shear reinforcement is no longer required if shear reinforcement is needed. The basic control perimeter u_1 is taken to be at a distance 2d from the loaded area (or column perimeter) and should be constructed so as to minimise its length.

Punching shear strength is the product of a shear stress times the area of the critical section under consideration. The full contribution of concrete to the design punching shear resistance of flat slabs without shear reinforcement at the basic control section is given by (CEN 2004):

$$V_{Rd,c} = \frac{0.18}{\gamma_c} \cdot \xi \cdot \left(100 \cdot \rho_l \cdot f_{ck}\right)^{1/3} \cdot u_1 \cdot d \tag{1}$$

In (1) γ_c is the concrete partial safety factor, ξ is the size effect factor (defined in Table 1 with d in mm), ρ_l is the ordinary reinforcement ratio, f_{ck} is the characteristic value of concrete compressive strength in MPa, u_1 is the length of basic control perimeter, and d is the mean effective depth of the slab calculated as shown in (2).

$$d = \left(d_x + d_y\right)/2 \tag{2}$$

The value of ρ_l is calculated as indicated in (3) as a mean value taking into account a slab width (C dimension, see Fig. 1) equal to the column width plus 3d each side of the column. Such reinforcement should anchor beyond the control perimeter being considered, u_1.

$$\rho_l = \sqrt{\rho_{lx} \cdot \rho_{ly}} \tag{3}$$

Where shear reinforcement is required the punching shear strength should be calculated in accordance with (4) where s_r is the radial spacing of perimeters of shear reinforcement, $f_{ywk,ef}$ is the effective characteristic strength of the punching shear reinforcement according to (5), γ_s is the partial safety factor for shear reinforcement steel, A_{sw} is the area of one perimeter of shear reinforcement around the column, and α is the angle between the shear reinforcement and the plane of the slab.

$$V_{Rd,cs} = \frac{3}{4} \cdot V_{Rd,c} + \left(\frac{3}{2} \cdot \frac{d}{s_r} \cdot \frac{f_{ywk,ef}}{\gamma_s} \cdot A_{sw} \cdot \sin\alpha \right) \tag{4}$$

With respect to CEB-FIP MC 90 and EN 1992-1-1 punching shear formulations, the original equations have been modified (Moreno 2010) in order to include the partial safety factor related to shear reinforcement steel, leading to (4). Therefore, equation (5) has been derived in order to account for the safety margin coupled with shear reinforcement (d in mm).

$$f_{ywk,ef} = 0.2875 \cdot (1000 + d) \leq f_{ywk} \tag{5}$$

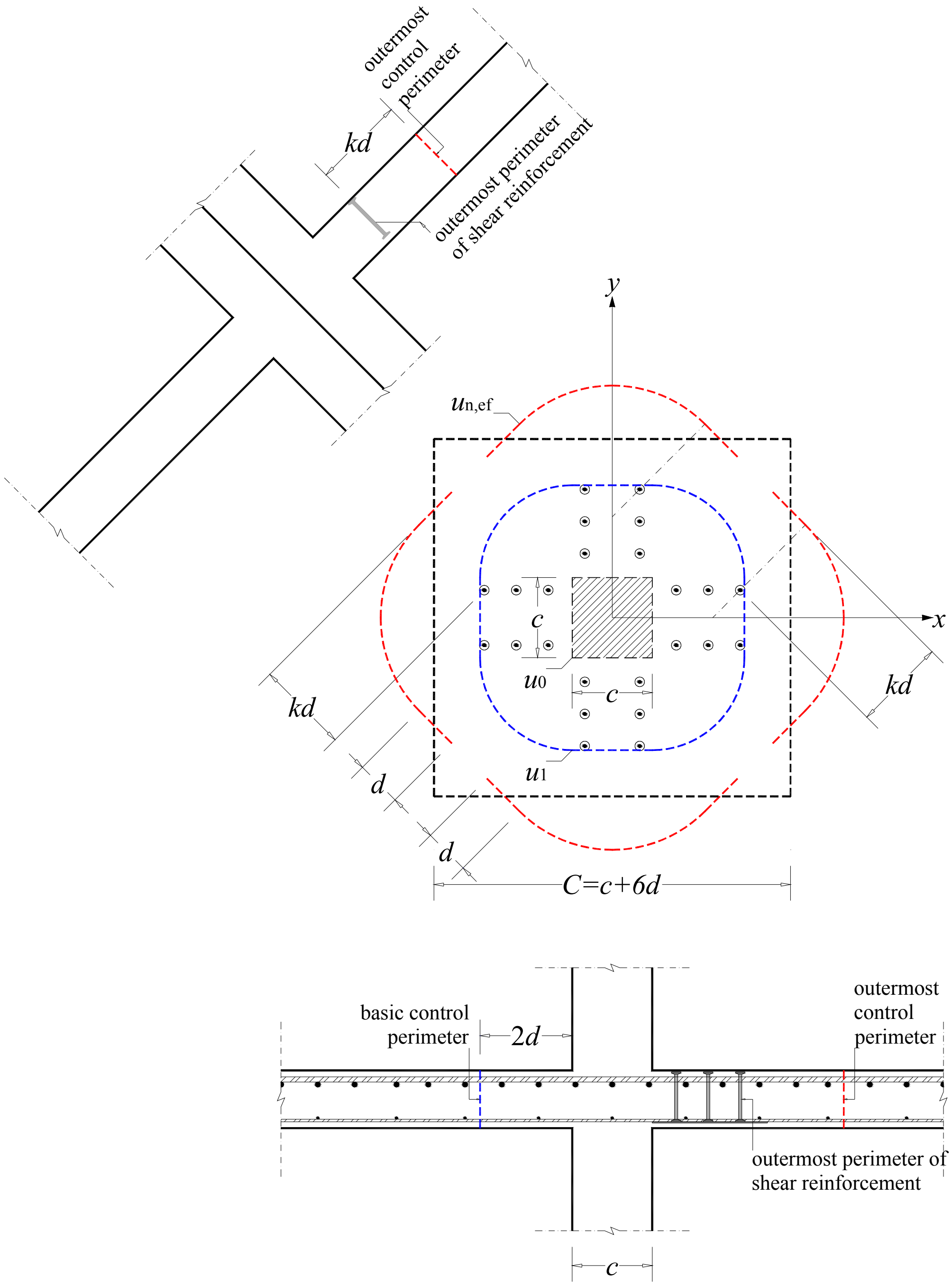

Fig. 1 u_0, u_1 and $u_{n,ef}$ control perimeters for interior square loaded areas according to the CEB-FIP MC 90 (CEB-FIP 1993) and EN 1992-1-1 (CEN 2004).

For slabs with transverse shear reinforcement the punching shear resistance should additionally be assessed for the outermost control section which defines the outermost control perimeter $u_{n,ef}$

(see Fig. 1). The outermost perimeter of shear reinforcement should be placed at a distance not greater than kd within $u_{n,ef}$ perimeter. According to EN 1992-1-1 the recommended value is k = 1.5 whereas CEB-FIP MC 90 recommends the value k = 2.

Although both code formulations are quite similar, main differences were identified and are summarised in Table 1.

Table 1
Limited parameters on punching shear design codes provisions

Parameter	Design code	
	CEB-FIP MC 90	Eurocode 2
Size effect factor, $\xi = 1+(200/d)^{1/2}$	-	≤ 2
Characteristic concrete strength, f_{ck}	$\leq$ 50 MPa	-
Ordinary reinforcement ratio, ρ_l	-	≤ 0.02
k factor (recommended values)	2.0	1.5

In order to fully compare both design code formulations a database has been derived compiling test results for slabs subjected to non-eccentric loading which failed in punching comprising both non-reinforced (128 experiments, see Fig. 2 to Fig. 4) and shear-reinforced slabs (38 experiments). In the following the materials partial safety factors are taken as $\gamma_c = \gamma_s = 1$ and the characteristic values of the material mechanical properties are replaced by the respective average value.

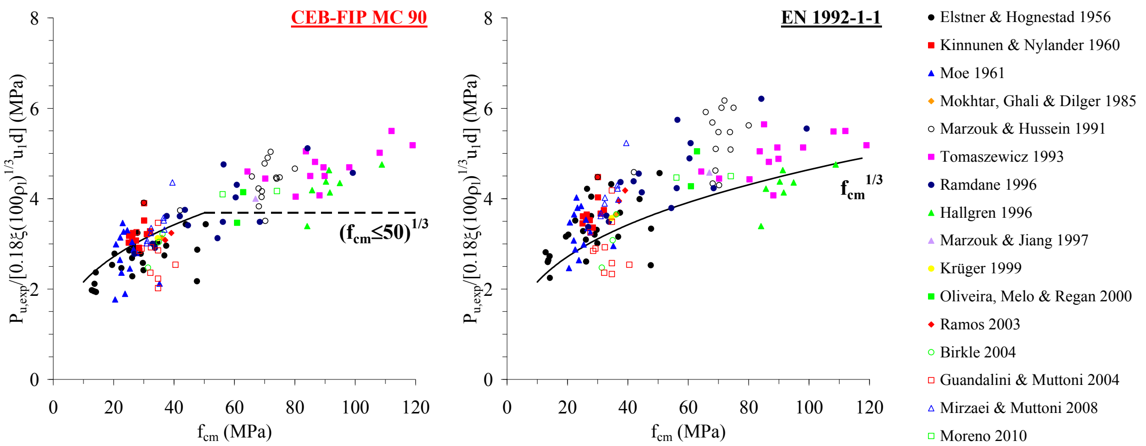

Fig. 2 Experimental punching shear failure load of shear non-reinforced slabs (non-eccentric loading) normalized regarding the average concrete compressive strength.

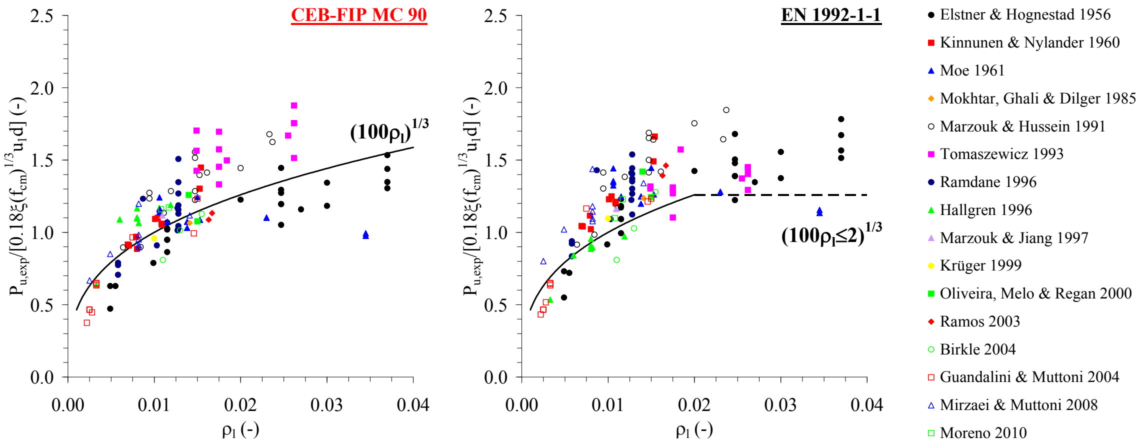

Fig. 3 Experimental punching shear failure load of shear non-reinforced slabs (non-eccentric loading) normalized regarding the ordinary reinforcement ratio.

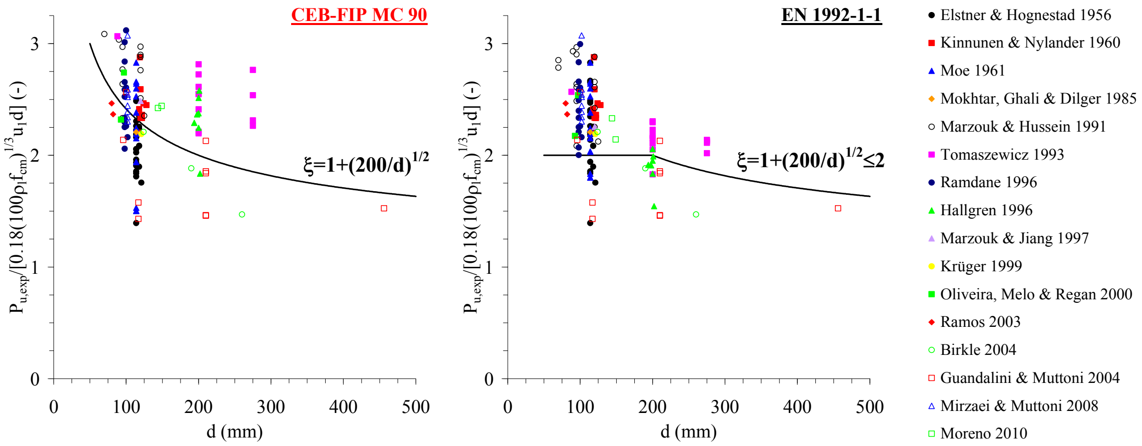

Fig. 4 Experimental punching shear failure load of shear non-reinforced slabs (non-eccentric loading) normalized regarding the size effect factor.

The range of collected values for average concrete compressive strength is between 12.8 MPa and 119 MPa, the mean effective depth of the slab varies from 70 mm to 456 mm, and the ordinary reinforcement ratio is comprised between 0.22% and 3.70%.

From the analysis of Fig. 2 to Fig. 4, one can notice that the CEB-FIP MC 90 condition $f_{ck} \leq 50$ MPa is needless so that the formulation can be extended to high performance concrete. As regards the ordinary reinforcement ratio, the EN 1992-1-1 imposes the limitation $\rho_l \leq 0.02$ which can certainly be understood as a concern about the ductility behaviour of the slab-column connections. Regarding the size effect factor, EN 1992-1-1 design code limitation $\xi \leq 2$ appears to be unnecessary. The authors propose as well to adopt the value $k = 2$. The enlargement of the distance comprised between the outermost perimeter of shear reinforcement $u_{n,ef}$ and the loaded (or column cross-section) perimeter from 1.5d to 2d can be justified by the test results of several authors (Elstner & Hognestad 1956; Voet, Dilger & Ghali 1982; Mokhtar, Ghali & Dilger 1985) who observed that the shear stress supported by concrete decreases with increasing distance from the column face and stabilizes at a distance of about 4d from the loaded area. Identical recommendation is done by the Danish national annex to Eurocode 2 (EN-1992-1-1 2007).

Current analysis results for both code formulations are summarised in Table 2.

Table 2
Comparison of test results with codes predictions as they stand

Experiments	Design code	$P_{u,exp}/V_{Rm}$			
		Min.	Max.	Average	CV
128 non-reinforced slabs	CEB-FIP MC 90	0.60	1.49	1.03	0.18
	Eurocode 2	0.70	1.54	1.14	0.17
38 shear-reinforced slabs	CEB-FIP MC 90	0.50	1.46	0.98	0.22
	Eurocode 2	0.54	2.16	1.18	0.38

Based on the comparative analysis, and aiming to reduce the high observed dispersion, a sensitivity analysis of the limiting parameters on the code provisions was developed. Consequently, following actions were taken:

1) CEB-FIP MC 90 provision $f_{ck} \leq 50$ MPa is ignored;
2) EN 1992-1-1 recommended value $k = 1.5$ is replaced by $k = 2$, and;
3) EN 1992-1-1 design code limitation $\xi \leq 2$ is not considered.

The above mentioned proposals were further computed and obtained results are summarised in Table 3. The overall effect of those proposals is thus far a significant reduction in standard deviation (CV) and in average value of the observed-to-predicted failure loads $P_{u,exp}/V_{Rm}$ ratio.

Table 3
Comparison of test results with codes predictions including proposals

Experiments	**Design code**	$P_{u,exp}/V_{Rm}$			
		Min.	**Max.**	**Average**	**CV**
128 non-reinforced slabs	CEB-FIP MC 90	0.60	1.28	0.98	0.13
	Eurocode 2	0.60	1.28	1.01	0.13
38 shear-reinforced slabs	CEB-FIP MC 90	0.44	1.38	0.98	0.22
	Eurocode 2	0.44	1.57	0.98	0.25

3 Experimental programme

3.1 Test specimens

Current experimental programme includes 4 RC square flat slab specimens 1100×1100 mm^2 wide and 100 mm height, which were designed so as the bending capacity prevail over the punching shear strength in order for slabs to fail in shear. The ordinary reinforcement ratio remained unchanged for all the tested slabs. Full details of specimen's geometry are presented in Fig. 5 where the ordinary reinforcement has been omitted in both the CFRP strengthened slabs for interpretation convenience.

The first specimen, denoted BC01, served as the non-strengthened reference slab. The second specimen, BCA1, included typical steel bent-down bars as punching shear reinforcement. The CFRP strengthening techniques were used in the third specimen, BCN1, which include 16 NSM cut-in in each direction, and in the EB specimen denoted BCG1 on which 6 CFRP laminates were bonded in each direction. Both the CFRP strengthened specimens were designed so as approximately similar effective reinforcement ratios were installed (see Table 5 and Table 6). Table 4 below summarises the chronological sequence of the experimental programme.

Table 4
Notation and RC slabs age at strengthening and testing

Slab	**Age at strengthening** (days)	**Age at experiment** (days)
BC01	-	31
BCA1	-	28
BCN1	36	41
BCG1	24	29

All the current specimens were reinforced on the top (tensile) side with orthogonal bending reinforcement using 8 mm diameter rebar spaced 50 mm. The main bars were folded up at both ends in order to promote better anchorage. The ratio ρ_l of ordinary reinforcement was 1.33% for all the tested specimens. A 20 mm concrete cover was guaranteed by using plastic rebar-to-formwork spacers.

Regarding BCA1 specimen, shear reinforcement comprising four bent-down bars in each direction were used spaced 50 mm. Shear reinforcement bars (8 mm diameter bars similar to the main reinforcement) were well anchored at their extremities and placed in two perimeters perpendicularly to the column face as shown in Fig. 5. The first perimeter of shear elements was positioned at a distance of approximately half effective depth (d/2) from the column face. The radial spacing of shear reinforcement perimeters was taken as $s_r \approx 0.7d$. According to (Hallgren 1996) the ratio of ordinary reinforcement should be modified (increased) with the part of the steel bent-down bars which act as main bending reinforcement over the loaded area (100×100×20 mm^3 steel plate denoted G in Fig. 5) as indicated:

$$\rho_{l,\text{mod}} = \rho_l + \frac{f_{ywk}}{f_{yk}} \cdot \frac{A_{sw}}{4 \cdot d \cdot C} \tag{6}$$

In (6) f_{ywk} is the characteristic value of the yielding stress of shear reinforcement steel, f_{yk} is the characteristic value of the yielding stress of ordinary reinforcement steel, A_{sw} is taken as the total cross-sectional area of the shear reinforcement, and dimension C is taken as defined in Fig. 1. The ultimate punching shear capacity of slab BCA1 is therefore predicted using (4) where $V_{Rd,c}$ is calculated with $\rho_{l,mod}$ = 1.86% instead of ρ_l leading to:

$$V_{Rd,c} = \frac{0.18}{\gamma_c} \cdot \xi \cdot \left(100 \cdot \rho_{l,\text{mod}} \cdot f_{ck}\right)^{1/3} \cdot u_1 \cdot d \tag{7}$$

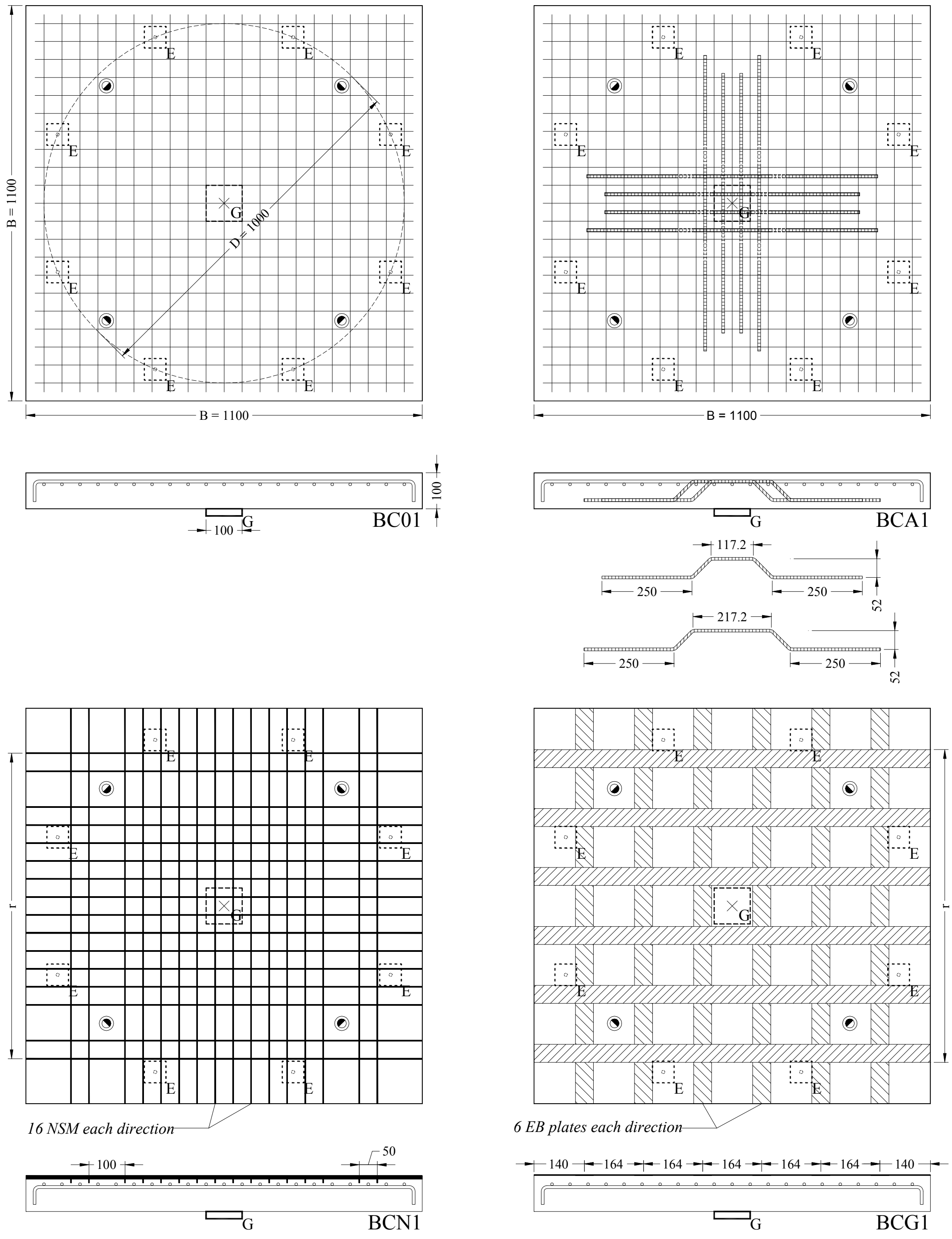

Fig. 5 Geometry of tested slabs (dimensions in mm).

For the CFRP strengthened slabs BCN1 and BCG1, the indirect effect of the CFRP reinforcement (which represents a reinforcement ratio increase of about 55% with respect to remaining non-strengthened specimens BC01 and BCA1) was accounted for according to the following. For brittle failures in punching, the ordinary reinforcement remains mostly elastic so that an equivalent effective depth d_{eq} can be computed as follows according to (Faria & al. 2014):

$$d_{eq} = d \cdot \frac{1 + \frac{\rho_{st}}{\rho_l} \cdot \frac{E_{st}}{E_s} \cdot \left(\frac{d_{st}}{d} \right)^2}{1 + \frac{\rho_{st}}{\rho_l} \cdot \frac{E_{st}}{E_s} \cdot \frac{d_{st}}{d}} \tag{8}$$

In (8) ρ_{st} is the strengthening reinforcement ratio, E_{st} is the modulus of elasticity of CFRP, and d_{st} is the distance between the compressed face and the centroid of the CFRP strengthening elements. As the bending stiffness of the slabs is therefore increased (Faria & al. 2014) propose the use of an effective reinforcement ratio ρ_{tot} which can be obtained as follows:

$$\rho_{tot} = \rho_l + \rho_{st} \cdot \frac{E_{st}}{E_s} \cdot \frac{r}{B} \cdot \left(\frac{d_{st}}{d} \right)^3 \tag{9}$$

In (9) B and r are taken as the slab dimension and the distance where the strengthening laminates are distributed, respectively (see Fig. 5). The obtained effective reinforcement ratios are summarised in Table 5 and Table 6 below for the BCN1 and BCG1 specimens, respectively.

Table 5
Main reinforcement ratio and geometry for BCN1 specimen

Layer #	**Material**	**Direction**	**d** (mm)	ρ_l (%)	**d** (mm)	ρ_{st} (%)	d_{st} (mm)	d_{eq} (mm)	ρ_{tot} (%)
1	Steel	y	68	1.33	72.0	-	-	76.7	2.07
2		x	76						
3	CFRP	x	85	-	-	0.45	90.0		
4		y	95						

Table 6
Main reinforcement ratio and geometry for BCG1 specimen

Layer #	**Material**	**Direction**	**d** (mm)	ρ_l (%)	**d** (mm)	ρ_{st} (%)	d_{st} (mm)	d_{eq} (mm)	ρ_{tot} (%)
1	Steel	y	68	1.33	72.0	-	-	78.4	2.08
2		x	76						
3	CFRP	x	100.6	-	-	0.32	101.2		
4		y	101.8						

3.2 Material properties

The tensile mechanical properties of the steel reinforcement were derived from representative samples testing. The yield and ultimate strength as well as the Young's modulus were measured and are as given in Table 7.

Table 7
Material properties of bending and shear reinforcement steel

Diameter (mm)	**Yield strength, f_{ym}** (N/mm^2)	**Ultimate strength, f_{um}** (N/mm^2)	**Young modulus, E_s** (kN/mm^2)
8	535	650	200

The concrete was designed to have a 28-day cube compressive strength of 30 MPa using 20 mm maximum aggregate size and a 0.55 free water-cement ratio. A 1% cement content of Sika ViscoCrete super-plasticiser was included in the concrete mix. A CEM II/B-M (T-LL) 42.5 cement was employed. Table 8 presents the average mechanical properties obtained on concrete samples (150×150×150 mm^3) which were tested on the experiment day of the respective slab specimen.

Conversion between cubic and cylinder compressive strength has been computed according to (Reineck & al. 2003):

$$f_{cm} = 0.79 \cdot f_{cm,cub} \tag{10}$$

Table 8
Mechanical properties of concrete mix

Slab	γ_{cm} (kN/m^3)	$f_{cm,cub}$ (N/mm^2)	f_{cm} (N/mm^2)
BC01	23.3	53.9	42.6
BCA1	23.4	44.6	35.3
BCN1	24.0	33.4	26.4
BCG1	23.0	34.1	27.0

The used CFRP plates were S&P CFK 150/2000 manufactured in Portugal by S&P Clever Reinforcement. These carbon laminates were used together with adhesive S&P Resin Epoxy 55 certified in accordance with EN 1504-4 (CEN 2004). Material properties of the CFRP plates used in current experimental tests are given in Table 9 (S&P 2014).

Table 9
Material properties and geometry of CFRP laminates

Parameter	**BCN1 specimen**	**BCG1 specimen**
Cross section (mm^2)	2.8×10	50×1.2
Modulus of elasticity, E_{st} (kN/mm^2)	165	165
Theoretical tensile strength at 0.8% elongation (N/mm^2)	1300	-
Recommended tensile strength for the design (N/mm^2)	-	1650
Tensile strength (N/mm^2)	2000	2000

3.3 CFRP strengthened specimens' preparation

The CFRP strengthened slabs were prepared following the instructions of the manufacturer. Regarding BCN1 slab, the slots of 5.5×20 mm^2 and 5.5×10 mm^2 were obtained using a circular saw (Fig. 6). For BCG1 specimen, a surface grinder was passed back and forth along pre-aligned paths until a uniform exposure of aggregate was achieved (Fig. 7). A vacuum cleaner allowed a clean surface from dust and loose particles to be obtained.

Fig. 6 BCN1 slots cutting.

Fig. 7 BCG1 surface prior to CFRP gluing.

3.4 Test procedure and instrumentation

All tests were conducted under concentrated loading (100×100 mm^2) and simply supported on eight points (60×60×10 mm^3 steel plates denoted E in Fig. 5) equally spaced along a D = 1000 mm diameter perimeter (see Fig. 5). Tests were performed using a servo-hydraulic test system by means of controlling the vertical force at 0.26 kN/s constant loading rate. The load was applied through a load-controlled hydraulic jack with a nominal range of 300 kN acting against a reaction strong slab.

A data acquisition system connected to a personal computer was used to control the loading and to collect test data (load, deflections and CFRP strains).

Externally, five LVDT (L1 to L5) were placed along the diameter D (see Fig. 5) in order to measure the deflections of the four tested slabs. Internally, five strain gauges (A to E) were laterally glued to CFRP laminates on BCN1 slab. Three strain gauges (A to C) were glued to the top surface of CFRP laminates on BCG1 specimen. The instrumentation is located as indicated in Fig. 8 where the truncated cone shaped surface taken accordingly to an estimated failure crack angle of 35 degrees is plotted.

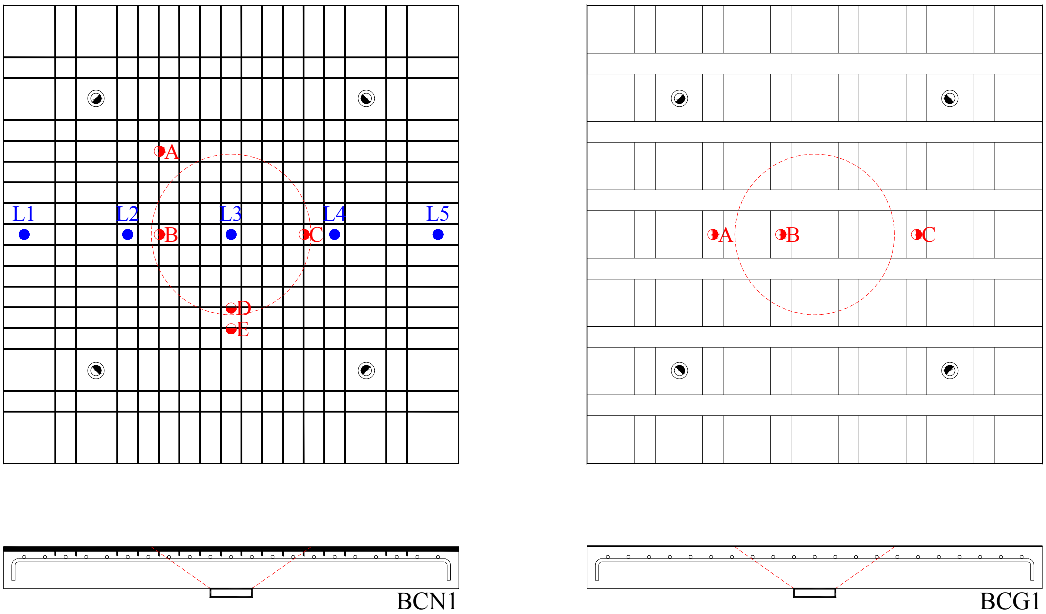

Fig. 8 Strain gauges and LVDT locations.

4 Experimental results

4.1 Failure load analysis

All the specimens failed in punching. In the following the materials partial safety factors are taken as $\gamma_c = \gamma_s = 1$ and the concrete compressive strength is taken as the respective average value. Experimental failure loads as well as predicted failure modes are indicated in Table 10.

According to (1) and to the actual value of concrete compressive strength, the failure loads of the four tested slabs were predicted based on punching shear approaches of both CEB-FIP MC 90 and Eurocode 2 considering non-strengthened specimens.

Design code approaches accurately predicted the failure load of the non-strengthened reference specimen BC01. Accordingly, $P_{u,exp}/V_{Rm,ns}$ ratio was computed for the remaining specimens and obtained values are indicated in Table 10. Regarding the slab reinforced with bent-down bars the enhancement on punching shear strength is estimated of about 29%. For the CFRP strengthened specimens, the NSM strengthening technique appears to be more effective (14% estimated enhancement) than EB technique (4% estimated strength increase) as regards punching capacity.

Furthermore, the actual predicted failure loads were calculated using (1) for BCA1 and CFRP strengthened specimens. For BCA1 specimen it was found that the minimum punching shear strength is attained at the outermost control section so that the outermost control perimeter $u_{n,ef}$ and the value k = 2 were computed in (1). Punching failure loads are consistently overestimated for shear-reinforced and CFRP strengthened specimens ($P_{u,exp}/V_{Rm}$ ratio in Table 10).

Table 10
Experimental and predicted failure loads

Slab	**Experimental failure load, $P_{u,exp}$** (kN)	**Non-strengthened (predicted) failure load, $V_{Rm,ns}$** (kN)	**Strengthened (predicted) failure load, V_{Rm}** (kN)	**$P_{u,exp}/V_{Rm,ns}$** (-)	**$P_{u,exp}/V_{Rm}$** (-)	**Predicted failure mode**
BC01	176.8	173.4	-	1.02	-	Punching
BCA1	209.8	162.9	243.5	1.29	0.86	Punching
BCN1	168.7	147.8	186.8	1.14	0.90	Punching
BCG1	155.0	149.0	194.4	1.04	0.80	Punching

4.2 Failure pattern analysis

The failure mode of the reference specimen, BC01, which was neither shear-reinforced nor strengthened with CFRP plates, was brittle as can be seen in Fig. 9 and Fig. 14.

Fig. 9 Cracking pattern and internal shear crack of slab BC01 after failure.

The failure mode of the steel shear-reinforced specimen, BA01, was also brittle as can be seen in Fig. 10.

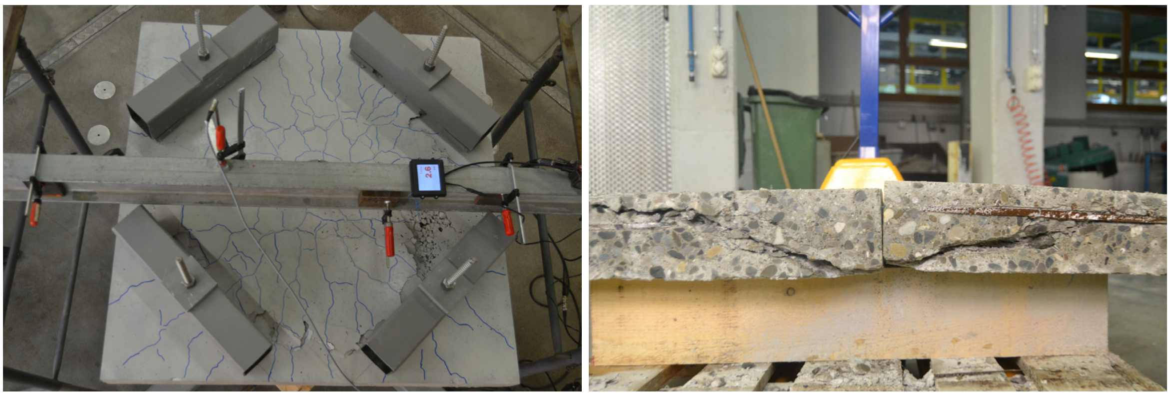

Fig. 10 Cracking pattern and internal shear crack of slab BA01 after failure.

Regarding both the CFRP strengthened specimens, Fig. 11 and Fig. 12 show the final post-experiment condition for BCN1 and BCG1 slabs, respectively. No evidence of debonding was observed in the NSM specimen. On the contrary, a pure punching shear failure was attained.

Fig. 11 Final aspect of BCN1 specimen after failure.

Fig. 12 Final aspect of BCG1 specimen after failure.

According to the literature the majority of the elements retrofitted using EB strengthening method experienced debonding as a failure method in spite of the efficiency of the strengthening technique.

As regards BCG1 specimen, no significant enhancement could hence be achieved to the overall shear stress using EB strengthening technique. A premature debonding of CFRP laminates located by the centre of the slab was identified at failure. Debonding did not actually occur at the edge of the slab but rather at an interior section. This suggests that the relative displacement perpendicular to the plane of the slab, which is due to the punching cone onset that precedes failure, set off a dowel effect that triggered the overall failure. Fig. 13 confirms the above referenced occurrence.

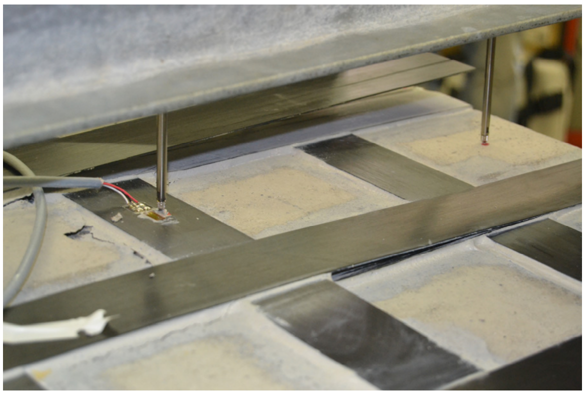

Fig. 13 Detail of local debonding on CFRP laminates of BCG1 specimen.

In fact, one can point out that the anchorage length of BCG1 specimen was insufficient. However, debonding-to-tensile failure length ratios were calculated. Table 11 shows that the specific anchorage lengths related to both the CFRP strengthened specimens are quite analogous.

Table 11
Specific anchorage lengths

Slab	**Technique**		**Debonding/tensile length** (m^{-1}/m)
BCN1	CFRP strengthened	NSM	0.71
BCG1		EB	0.83

4.3 Load-deflection characteristics

The deflections measured at the centre of the slabs followed an almost linear starting relationship with applied load as shown in the following (Fig. 14 to Fig. 17). In fact, the load-deflection relationships are nearly linear up to the first cracking occurrence in all the slabs.

No subsequent considerable reduction in stiffness was detected, except for the strengthened slabs BCN1 and BCG1 which is due to the higher effective reinforcement ratio (see section 3.1).

The load-deflection curves have thus confirmed the brittle nature of the failure of slabs collapsing in punching mode. The failure mode of the non-strengthened reference specimen BC01, which was neither shear-reinforced nor CFRP laminates strengthened, was particularly brittle as can be seen in Fig. 14.

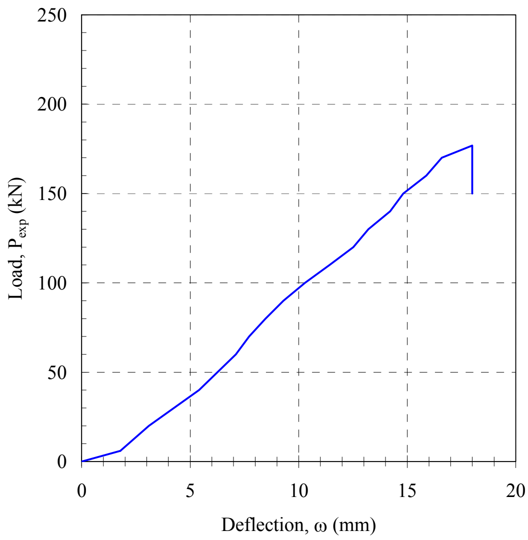

Fig. 14 Load-central deflection of the BC01 slab.

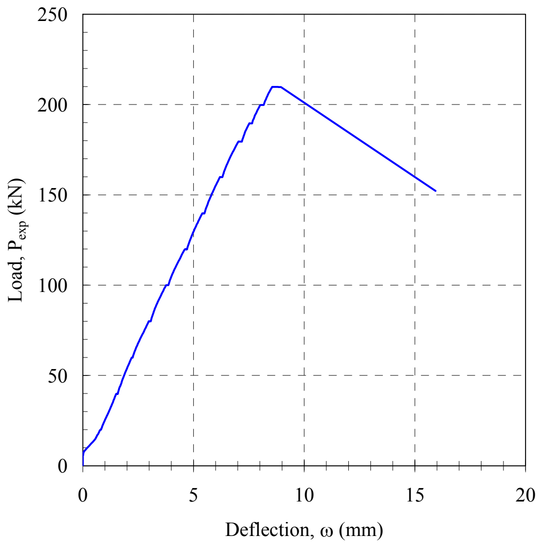

Fig. 15 Load-central deflection of the BCA1 slab.

Ductility enhancement due to bent-down bars was not noticeable on the shear-reinforced slab response (Fig. 15).

Concerning the NSM strengthened specimen (Fig. 16), the load-deflection curve arched near the end of the experiment while the existing cracks widened and propagate towards the compression zone. The stiffness of both the CFRP strengthened specimens (Fig. 16 and Fig. 17) was markedly increased when compared to the non-strengthened reference specimen BC01 due to the enhanced effective reinforcement ratio. In effect, central deflections of only 3 to 4 mm were measured.

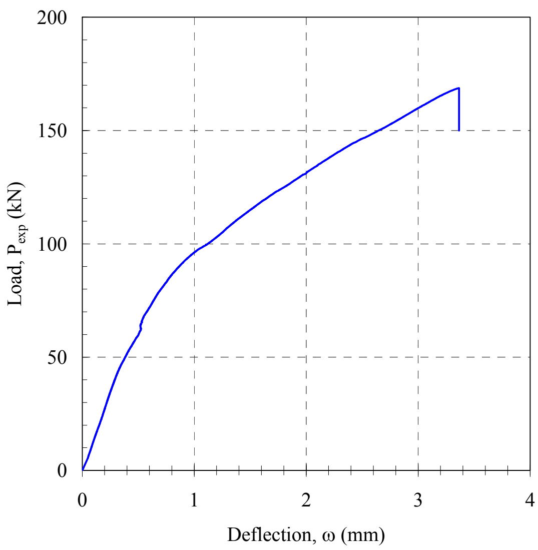

Fig. 16 Load-central deflection of the BCN1 slab.

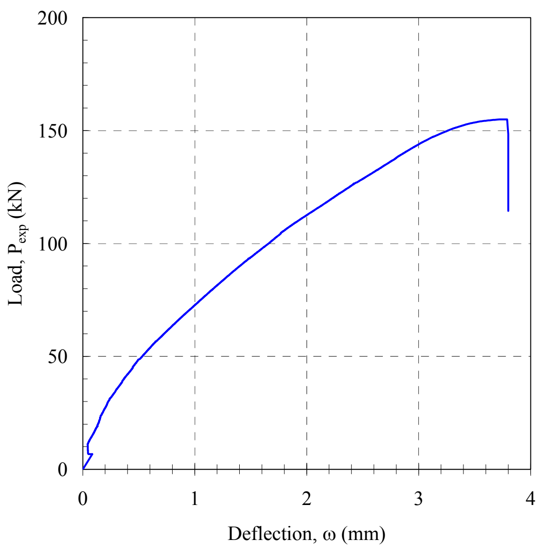

Fig. 17 Load-central deflection of the BCG1 slab.

4.4 CFRP strains analysis

The load-strain relationships for the CFRP reinforcement of strengthened specimens BCN1 and BCG1 are shown in Fig. 18 and Fig. 19, respectively (strain gauges locations indicated in Fig. 8). Assuming the strain compatibility in the strengthened slabs cross section, one can infer that ordinary reinforcement did not reach yielding on both the CFRP strengthened specimens, as maximum strains of about 0.15% to 0.20% were measured.

Regarding the NSM strengthened specimen (Fig. 18), CFRP strains remained of negligible magnitude until cracking initiation. Centrally located strain gauges (B to E, see Fig. 8) show analogous responses. Additionally, the comparison of collected data in strain gauges A and B, which are located on the same CFRP laminate, indicate that the deformation decreases sharply with increasing distance to loaded area.

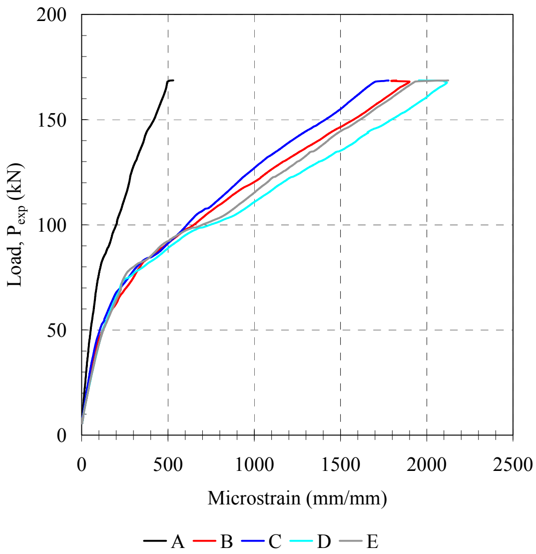

Fig. 18 Load-strain relationship for CFRP laminates of BCN1 specimen.

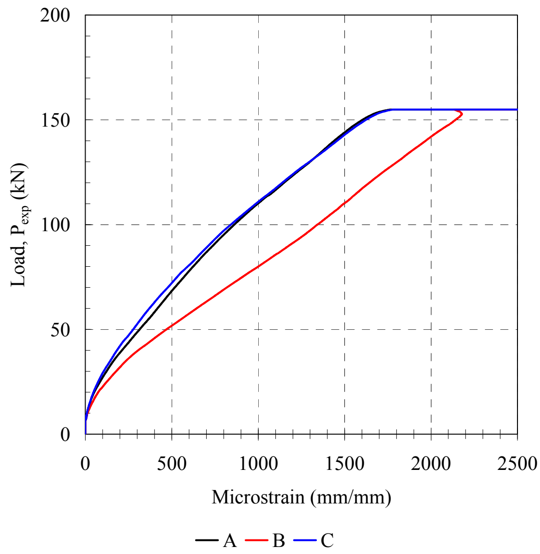

Fig. 19 Load-strain relationship for CFRP laminates of BCG1 specimen.

As regards the EB strengthened specimen (Fig. 19), the recorded strains confirm the symmetry of the experimental test as coincident strains were obtained in strain gauges A and C.

5 Conclusions

The current work intends to assess the performance of different solutions regarding slabs' strengthening against punching. Firstly, a specimen was strengthened before casting using steel bent-down bars. For existing slabs, two different design solutions were investigated. One of them consisted in gluing CFRP laminates on slab's surface while the other design was based on introducing CFRP laminated strips into slits cute on the concrete cover, bonded to concrete using epoxy adhesive (NSM technique). In order to compare these two techniques similar CFRP reinforcement ratios were adopted.

Further to current investigation, following conclusions can be drawn:

- Proposals are made for both CEB-FIP MC 90 and EN 1992-1-1 code provisions regarding punching shear strength in order to reduce the standard deviation and the average values of the relationship between experimental and predicted punching failure loads;
- Good agreement is found regarding the observed-to-predicted failure load ratios $P_{u,exp}/V_{Rm}$ when the above referred proposals are taken into account;
- Flat slab specimen reinforced with steel bent-down bars showed an enhanced punching shear strength of approximately 29% when compared with non-strengthened reference slab;

- The NSM specimen presented an enhanced punching shear capacity strength that can be estimated as 14%. This value should be considered relatively large when compared with results from other researchers;
- No evidence of debonding was observed in the NSM specimen. On the contrary, a pure punching shear failure was obtained;
- The NSM CFRP strips presented an enhanced performance compared to EB CFRP plates regarding punching shear failure. In the later, premature surface debonding of the laminates triggered the specimen's failure;
- On the EB CFRP specimen, no significant enhancement (4%) could be achieved to the overall shear stress using this strengthening scheme. A premature debonding of CFRP laminates was detected at the punching cone onset that preceded failure;
- Ordinary reinforcement clearly remained elastic on the four tested slabs as maximum strains of about 0.15% to 0.20% were measured on both the CFRP strengthened specimens.

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References

ACI (2008). ACI 440.2R-08 - Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, Reported by ACI Committee 440: 76.

Barros, J. A. O. d. & al. (2006). "Assessing the effectiveness of embedding CFRP laminates in the near surface for structural strengthening." Construction and Building Materials 20: 478-491.

Birkle, G. (2004). Punching of Flat Slabs: The Influence of Slab Thickness and Stud Layout. Department of Civil Engineering. Calgary, Alberta, The University of Calgary. PhD Thesis: 152.

CEB-FIP (1993). Model Code 1990. Comité Euro-International du Béton. Lausanne, Thomas Telford Services Ltd: 437.

CEN (2004). EN 1992-1-1 : Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. Brussels, Central Secretariat.

CEN (2004). EN 1504-4 : Products and systems for the protection and repair of concrete structures. Definitions, requirements, quality control and evaluation of conformity. Structural bonding. Brussels, Central Secretariat.

Elstner, R. C. & Hognestad, E. (1956). "Shearing Strength of Reinforced Concrete Slabs." ACI Journal Vol. 53: 29-58.

EN-1992-1-1 (2007). EN 1992-1-1 DK NA:2007. National Annex to Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. Denmark.

Faria, D. M. V. & al. (2014). "On the efficiency of flat slabs strengthening against punching using externally bonded fibre reinforced polymers." Construction and Building Materials 73: 366-377.

Guandalini, S. & Muttoni, A. (2004). Essais de poinçonnement symétrique des dalles en béton armé sans armature à l'effort tranchant - Punching tests on symmetrical reinforced concrete slabs without shear reinforcement. 00.03, Rapport 00.03-R1. Lausanne, École Polytechnique Fédérale de Lausanne: 78.

Hallgren, M. (1996). Punching Shear Capacity of Reinforced High Strength Concrete Slabs. Department of Structural Engineering. Stockholm, Sweden, Royal Institute of Technology. Doctoral Thesis: 206.

Kinnunen, S. & Nylander, H. (1960). Punching of Concrete Slabs Without Shear Reinforcement. Transactions of the Royal Institute of Technology - Stockholm, Sweden, N.º 158. Göteborg: 112.

Krüger, G. (1999). Résistance au poinçonnement excentré des planchers-dalles. Lausanne, École Polytechnique Fédérale de Lausanne. PhD Thesis: 191.

Marzouk, H. & Hussein, A. (1991). "Experimental Investigation on the Behaviour of High-Strength Concrete Slabs." Structural Journal Vol. 88, No. 6(ACI): 701-713.

Marzouk, H. & Jiang, D. (1997). "Experimental Investigation on Shear Enhancement Types for High-Strength Concrete Plates." Structural Journal Vol. 94, No. 1(ACI): 49-58.

Mirzaei, Y. & Muttoni, A. (2008). Tests on the Post-Punching Behavior of Reinforced Concrete Flat Slabs. Institut de Structures - Laboratoire de Construction en Béton. Lausanne, École Polytechnique Fédérale de Lausanne: 58.

Moe, J. (1961). "Shearing Strength of Reinforced Concrete Slabs and Footings under Concentrated Loads." Portland Cement Association Bulletin D47(Research and Development Laboratories): Skokie, 144.

Mokhtar, A.-S., Ghali, A. & Dilger, W. (1985). "Stud Shear Reinforcement for Flat Concrete Plates." ACI Structural Journal Vol. 82, No. 5(ACI): 676-683.

Moreno, C. (2010). Flat slabs. Contributions for the understanding of their behaviour. Department of Civil Engineering. Porto, Faculty of Engineering, University of Porto. PhD Thesis: 220.

Nigro, E., Ludovico, M. D. & Bilotta, A. (2008). FRP-Concrete debonding: Experimental tests under cyclic actions. The 14th World Conference on Earthquake Engineering, Beijing, China.

Oliveira, D. R., Melo, G. S. & Regan, P. E. (2000). "Punching Strengths of Flat Plates with Vertical or Inclined Stirrups." ACI Structural Journal Vol. 97, No. 3(ACI): 485-491.

Ramdane, K. E. (1996). Punching Shear of High Performance Concrete Slabs. 4th International Symposium on Utilization of High-strength/High-performance Concrete. Paris, Presses de L'école Nationale des Ponts et Chaussées: 1015-1026.

Ramos, A. P. (2003). Punçoamento em Lajes Fungiformes Pré-esforçadas. Lisboa, Universidade Técnica de Lisboa. Tese de Doutoramento: 292.

Reineck, K.-H. & al. (2003). "Shear Database for Reinforced Concrete Members without Shear Reinforcement." ACI Structural Journal Vol. 100, No. 2: 240-249.

S&P (2014). Technical Data Sheet, S&P Clever Reinforcement Company AG.

Tomaszewicz, A. (1993). High-strength Concrete SP2 - Plates and Shells. Report 2.3, Punching Shear Capacity of Reinforced Concrete Slabs. Report No. STF70 A93082. Trondheim, SINTEF: 36.

Voet, A. F. v. d., Dilger, W. H. & Ghali, A. (1982). "Concrete flat plates with well-anchored shear reinforcement elements." Canadian Journal of Civil Engineering Vol. 9(NRC): 107-114.