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Recent Developments in High Strain Rate Mechanics and Impact Behavior of Concrete

Editors:
Eric Jacques and Mi G. Chorzepa

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PREFACE

Recent Developments in High Strain Rate Mechanics and Impact Behavior of Concrete

This Symposium Volume reports on the latest developments in the field of high strain rate mechanics and behavior of concrete subject to impact loads. This effort supports the mission of ACI Committee 370 "Blast and Impact Load Effects" to develop and disseminate information on the design of concrete structures subjected to impact, as well as blast and other short-duration dynamic loads. Concrete structures can potentially be exposed to accidental and malicious impact loads during their lifetimes, including those caused by ballistic projectiles, vehicular collision, impact of debris set in motion after an explosion, falling objects during construction and floating objects during tsunamis and storm surges. Assessing the performance of concrete structures to implement cost-effective and structurally-efficient protective measures against these extreme impacting loads necessitates a fundamental understanding of the high strain rate behavior of the constituent materials and of the characteristics of the local response modes activated during the event.

This volume presents fourteen papers which provide the reader with deep insight into the state-of-the-art experimental research and cutting-edge computational approaches for concrete materials and structures subject to impact loading. Invited contributions were received from international experts from Australia, Canada, China, Czech Republic, Germany, South Korea, Switzerland, and the United States. The technical papers cover a range of cementitious materials, including high strength and ultra-high strength materials, reactive powder concrete, fiber-reinforced concrete, and externally bonded cementitious layers and other coatings. The papers were to be presented during two technical sessions scheduled for the ACI Spring 2020 Convention in Rosemont, Illinois, but the worldwide COVID-19 pandemic disrupted those plans.

The editors thank the authors for their outstanding efforts to showcase their most current research work with the concrete community, and for their assistance, cooperation, and valuable contributions throughout the entire publication process. The editors also thank the members of ACI Committee 370, the reviewers, and the ACI staff for their generous support and encouragement throughout the preparation of this volume.

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On the Rate Sensitive Fracture Behavior of Strain-Hardening Cement-Based Composites (SHCC) Depending on Fiber Type and Matrix Composition

Iurie Curosu, Viktor Mechtcherine, Daniele Forni, Simone Hempel and Ezio Cadoni

Synopsis: Strain-hardening cement-based composites (SHCC) represent a special type of fiber-reinforced concretes, whose post-elastic tensile behavior is characterized by the formation of multiple, fine cracks under increasing loading up to failure localization. The high inelastic deformability in the strain-hardening phase together with the high damage tolerance and energy dissipation capacity make SHCC promising for applications involving dynamic loading scenarios, such as earthquake, impact or blast.

However, the main constitutive phases of SHCC, i.e. matrix, fibers and interphase between them, are highly rate sensitive. Depending on the SHCC composition, the increase in loading rates can negatively alter the balanced micromechanical interactions, leading to a pronounced reduction in strain capacity. Thus, there is need for a detailed investigation of the strain rate sensitivity of SHCC at different levels of observation for enabling a targeted material design with respect to high loading rates.

The crack opening behavior is an essential material parameter for SHCC, since it defines to a large extent the tensile properties of the composite. In the paper at hand, the rate effects on the crack opening and fracture behavior of SHCC are analyzed based on quasi-static and impact tensile tests on notched specimens made of three different types of SHCC. Two SHCC consisted of a normal-strength cementitious matrix and were reinforced with polyvinyl-alcohol (PVA) and ultra-high molecular weight polyethylene (UHMWPE) fibers, respectively. The third type consisted of a high-strength cementitious matrix and UHMWPE fibers. The dynamic tests were performed in a split Hopkinson tension bar and enabled an accurate description of the crack opening behavior in terms of force-displacement relationships at displacement rates of up to 6 m/s (19.7 ft/s).

Keywords: SHCC, fiber reinforcement, strain-hardening, PVA, UHMWPE, impact, split Hopkinson tension bar, fracture energy

High Strain Rate Properties of CFRP Sheets Surface Bonded to Concrete

Jonathan Harman, Emmanuella O. Atunbi, Alan Lloyd

Synopsis: Many common building materials, such as concrete and steel, are understood to experience a change in apparent material properties under high strain rates. This effect is often incorporated into impact and blast design by using dynamic increase factors (DIFs) that modify properties of the material such as strength and stiffness when subjected to high strain rates. There is currently limited guidance on dynamic properties of fiber reinforced polymer (FRP) sheets bonded to concrete. Since FRP is a common retrofit material for blast and impact load vulnerable structures, it is important to have a full understanding on the behaviour of the FRP material and of the composite action between the FRP sheet and the substrate it is bonded to. Important parameters for blast and impact resistant design of reinforced concrete structures retrofitted with surface bonded FRP include dynamic measures of debonding strain, development length, and bond stress. This paper presents the results of an experimental program measuring the dynamic properties of carbon fiber reinforced polymer (CFRP) sheets bonded to concrete under impact induced high strain rates.

A series of rectangular concrete prisms were cast and fitted with surface bonded CFRP sheets to facilitate pull-out shear tests that directly measure the FRP to concrete bond. The bonded length of the CFRP sheet was variable with three different lengths explored. A series of static tests have been conducted to measure the strain fields on the FRP sheets under load up to failure. These strain fields, which were measured with digital image correlation techniques, were used to determine development length, bond stress, and ultimate strain of the FRP sheet prior to debonding. A companion set of prisms have also been cast and will be tested under impact loading to explore the same properties at high strain rates of around 1 s-1. Initial test results indicate a potential increase in both ultimate strain and bond stress, and a decrease in development length under high strain rates. The results of the larger study will be compiled and, when compared with the static companion set, be used to propose DIFs for FRP sheets bonded to concrete for use in design in high strain rate applications.

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Keywords: FRP sheet, CFRP, surface bonded; high strain rate

Using Steel Fibres to Increase the Projectile Impact Resistance of Cementitious Composites

Radoslav Sovják, Sebastjan Kravanja, Jan Zatloukal

Synopsis: Steel fibres in cementitious composites play a crucial role in making structures less susceptible to the damage caused by projectile impacts. A synergistic effect is achieved when steel fibres and an otherwise brittle cementitious matrix are blended together to produce a high-performance fibre-reinforced cementitious composite with enhanced ductility and strength. These composites also display strain hardening in tension, which leads to enhanced energy absorption and dissipation capacity. In this study, in-service 7.62 × 39 mm [0.28 × 1.54 in.] cartridges were used as projectiles. The muzzle velocity and weight of the projectiles were 710 m/s [2329 ft/s] and 8.04 grams [0.284 oz], respectively. Projectiles were shot with a stationary semi-automatic rifle into specimens made of high-performance fibre-reinforced cementitious composites with various fibre volume contents. Fibres used in this study were straight with a smooth surface. The aspect ratio of the fibre was 108:1 and corresponding dimensions were 14×0.13 mm [0.55×0.005 in.]. The tensile strength of the fibres was 2,800 MPa [406 ksi] and the modulus of elasticity was 210 GPa [30,458 ksi]. Owing to their exceptional mechanical properties, the fibres played a key role in controlling the response of the specimens when impacted by projectiles. The highest fibre volume content used in this study was 2% by volume; the cube compressive strength of the resulting mixture was 144 MPa [20.9 ksi]. Specimens were examined for the possible presence of spalling, scabbing, cracking, or full perforation. Depth of penetration, crater area, and crater volume were also tested. Results showed that steel fibres, due to the aforementioned synergistic effect with a cementitious matrix, notably protected specimens from erosion and significantly reduced cratering damage.

Keywords: cementitious composites, crater area, crater volume, depth of penetration, projectile impact, shear crack analysis, steel fibres

Predicting the Response of Concrete Barriers to Rigid Projectile Impacts Using AEM

Tarek Kewaisy, Ayman Elfouly, and Ahmed Khalil

Synopsis: For protective construction applications involving high-velocity projectile impacts, design engineers rely on properly designed reinforced concrete barriers to provide the necessary resistance to penetration. Typically dynamic testing, analytical, semi-empirical and/or computational approaches are called upon to properly handle this highly complex physical problem. The presented research evaluates the use of Applied Element Method (AEM), implemented in Extreme Loading for Structures (ELS) software, to predict the localized damage and penetration of concrete slabs due to high-velocity normal impacts of rigid projectiles. Two validation cases were considered involving different concrete and reinforcing rebar material properties and projectile impact velocities. The applicability of AEM simulations was validated by comparing predicted damage and projectile penetrations to corresponding observations and measurements obtained during impact testing. A limited parametric study including seven analytical cases was performed to investigate the effects of varying concrete strengths, reinforcement arrangements and concrete thickness on the penetration resistance of concrete targets. To achieve this, three concrete classes; Normal Strength Concrete (NSC), Medium Strength Concrete (MSC) and High Strength Concrete (HSC), three reinforcement configurations (unreinforced, single-layer larger bar, double-layers) and larger thickness were considered. The application of the engineering-oriented AEM/ELS software was found to provide impact response predictions that are in good agreement with physical test results. The results of the parametric study confirmed the advantages of using higher concrete strengths and higher reinforcement ratios in improving the penetration resistance and reducing the scabbing damage of reinforced concrete barriers.

Keywords: Predicting; Rigid Projectile; Impact; Penetration; Damage; Concrete; Barrier; Applied Element Method (AEM); Extreme Loading for Structures (ELS)

Cracked Continuum Modeling of Reinforced Concrete Elements under Impact

Serhan Guner, Trevor D. Hrynyk, and Andac Lulec

Synopsis: Current computational modeling approaches used to evaluate the impact-resisting performance of reinforced concrete infrastructure generally consist of high-fidelity modeling techniques which are expensive in terms of both model preparation and computation cost; thus, their application to real-word structural engineering problems remains limited. Further, modeling shear, erosion, and perforation effects presents as a significant challenge, even when using expensive high-fidelity computational techniques. To address these challenges, a simplified nonlinear modeling methodology has been developed. This paper focuses on this simplified methodology which employs a smeared-crack continuum material model based on the constitutive formulations of the Disturbed Stress Field Model. The smeared-crack model has the benefit of simplifying the modeling process and reducing the computational cost. The total-load, secant-stiffness formulation provides well-converging and numerically stable solutions even in the heavily damaged stages of the responses. The methodology uses an explicit time-step integration method and incorporates the effects of high strain rates in the behavioral modeling of the constituent materials. Structural damping is primarily incorporated by way of nonlinear concrete and reinforcement hysteresis models and significant second-order mechanisms are considered. The objective of this paper is to present a consistent reinforced concrete modeling methodology within the context of four structural modeling procedures employing different element types (e.g., 2D frames, 3D thick-shells, 3D solids, and 2D axisymmetric elements). The theoretical approach common to all procedures and unique aspects and capabilities of each procedure are discussed. The application and verification of each procedure for modeling different types of large-scale specimens, subjected to multiple impacts with contact velocities ranging from 8 m/s (26.2 ft/s) to 144 m/s (472 ft/s), and impacting masses ranging from 35 kg (77.2 lb) to 600 kg (1323 lb), are presented to examine their accuracy, reliability, and practicality.

Keywords: axisymmetric, erosion, frame, missile, perforation, shear, shell, smeared, solid, strain rates.

Distinguished Impact Response of Hollow Reinforced Concrete Beams under Impact Loading

Thong M. Pham, Tin V. Do, and Hong Hao

Synopsis: This study experimentally and numerically investigated the impact responses of reinforced concrete (RC) beams with a rectangular hollow section (HCB) in comparison with a rectangular solid section (SCB). Experimental tests of the two types of RC beams were firstly conducted under the drop-weight impact of a 203.5-kg-solid-steel projectile. Numerical models of the beams under impact loads were then developed in the commercial software namely LS-DYNA and carefully verified against the experimental results. The numerical models were then used to investigate the stress wave propagation in the two beams. The effect of the top flange depth, contact area, and impact velocity on the impact responses of the beams was also investigated. The experimental and numerical results in this study showed that although the two beams were designed with similar reinforcement ratio, their impact responses were considerably different, especially when the shear failure dominated the structural response. The HCB exhibited a smaller peak impact force but higher lateral displacement than the SCB when these beams were subjected to the same impact condition. Besides, more shear cracks were observed on the HCB while that of SCB has more flexural cracks. Furthermore, the decrease of the top flange depth of the hollow section and the increase of the impact velocity changed the failure modes of the two beams from flexural failure to shear failure with concrete scabbing. The change of the contact area also shifted the failure mode of the beam from global response to direct shear, inclined shear, punching shear and concrete scabbing at the top flange of the section close to the impact location.

Keywords: Impact response; Concrete beam; Drop-weight tests; Numerical Simulation; Hollow beams; Shear Failure

Damage Accumulation Comparison of Fiber-Reinforced Concrete Using Repeated Drop Impact Testing

Andrew D. Sorensen, Robert J. Thomas, Ryan Langford and Abdullah Al-Sarfin

Synopsis: The impact resistance of concrete is becoming an increasingly important component of insuring the durability and resilience of critical civil engineering infrastructure. Design engineers are not currently able to use impact resistance as a performance-based specification in concrete due to a lack of a reliable standardized impact test for concrete. An improved method of the ACI standard, ACI 544.2R-89 Measurement of Properties of Fiber Reinforced Concrete, is developed that provides a resistance curve as a function of impact energy and number of blows (N) to failure. The curve provides information about the life cycle (N) under repeated sub-critical impact events and an estimate of the critical impact energy (where N=1), whereas the previous method provided only a relative value. The generated impact-fatigue curve provides useful information about damage accumulation under repeated impact events and the effectiveness of the fiber-reinforcement. In this paper, the improved method is demonstrated for three fiber types: steel, copolymer polypropylene, and a monofilament polypropylene. Additionally, the analytical solution for the specimen geometry is given as well as the theoretical considerations behind the development of the impact-life curve. The use of a specimen geometry provides a path to generalize the test results to full-scale structures.

Keywords: drop-weight impact, damage prediction, fiber reinforced concrete, impact testing standards

Response of Reinforced Concrete Columns against Hypervelocity Impacts by EFPs

Alex Remennikov and Edward Chern Jinn Gan

Synopsis: Explosively formed projectiles (EFP) are one of the most severe explosive and impact loading threats for civil infrastructure and military vehicles. EFP warheads are commonly found in conventional anti-tank weapons. They are also regularly used by insurgent forces against armoured vehicles in conflict-affected countries. The energy of EFPs is significantly greater than that of large calibre ammunition, such that a threat is posed to the occupants of armoured vehicles both by perforation and spalling of the armour. This paper aims to present new experimental results of the hypervelocity impact of EFPs on reinforced concrete (RC) columns to demonstrate the vulnerability of infrastructure to EFP improvised explosive devices (EFP-IEDs). As a possible mitigation measure of threat against EFPs, an RC column was retrofitted with a steel-jacket. The ability of a steel-jacket to minimise RC column damage was evaluated where it was found to minimise damage to the RC column and contain concrete fragments. Three-dimensional numerical simulations were performed to elucidate the different stages of EFP interaction with the RC columns. No previously published results on the EFP terminal ballistic performance of RC columns have been found in the open literature.

Keywords: explosively formed projectiles, improvised explosive devices, steel jacketing, terminal ballistic, Ansys, smooth particle hydrodynamics

Impact Response of SC Panels under Local Punching Failure: Experiments and FE Analyses

Quanquan Guo, Chengwei Guo, Xuqiang Dou，Chuanchuan Hou

Synopsis: In the past, the study of low-velocity impact response of steel-concrete composite panels (SC) mainly focused on the overall flexure failure mode. To study the impact dynamic response of SC panels under the local punching failure mode, a drop hammer impact test of ten SC panels was carried out in this paper. The influence of the impact energy, impact momentum, and axial compression ratio was investigated. With the increase of impact energy, five damage patterns appeared in turn under the local punching failure mode. And the whole response process could be divided into five stages. It was found that the change of impact momentum had little influence on SC panels, but axial compressive preload could improve the stiffness and the impact capacity of SC panels to a certain extent. A finite element (FE) model based on LS-DYNA was then established and it could simulate the test process reasonably well. A mechanical analysis of the dynamic response process was carried out with the numerical model, including a parametric study on the influence of the axial compression ratio.

Keywords: steel-concrete composite panel (SC); local punching failure mode; dynamic response; finite element (FE) model; axial compression ratio

STRUCTURAL BEHAVIOR OF TL-4 RECYCLED TIRE CHIP AND FIBER REINFORCED CONCRETE SINGLE SLOPE BARRIERS

Grace Darling, Stephan A. Durham, and Mi G. Chorzepa

Synopsis: Concrete median barriers (CMB) are installed to decrease the overall severity of traffic accidents by producing higher vehicle decelerations. In 2016, an update to the AASHTO Manual for Assessing Safety Hardware (MASH) saw a 58% increase in impact severity of test level 4 (TL-4) impact conditions when compared to the NCHRP Report 350 testing criteria. This study investigates the use of fiber-reinforced rubberized CMBs in dissipating the impact energy to improve driver safety involved in crashed vehicles. Two full-scale barrier prototypes with shear keys were constructed and tested under impact conditions in a laboratory setting. Compared to the Georgia Department of Transportation specified single-slope barrier, the fiber-reinforced rubberized concrete mixture, a design with 20% replacement of the coarse aggregate by volume with recycled rubber tire chips and a 1.0% steel fiber addition, was evaluated based on its performance in toughness, energy absorption capacity, and its recoverable deformation. It is concluded that the TC20ST1 barrier performed as well as the control barrier at the impact load of 150.0 kips (667.2 kN), with neither barrier experiencing any visible damage.

Keywords: Single Slope Barrier, Rubberized Concrete, Fiber Reinforced Concrete (FRC), Dynamic Impact, Recycled Tire Chips, Steel Fibers, Concrete Median Barrier (CMB), MASH Testing

Impact Performance of Recycled Rubber Tire Chip and Fiber-Reinforced Cementitious Composites

Victor Lopez, Mi G. Chorzepa, and Stephan A. Durham

Synopsis: This paper presents the drop-weight impact performance of recycled tire chip and fiber-reinforced cementitious composites. Emphasis is placed on maximizing the energy dissipation capacity of rubberized fiber reinforced concrete (FRC) mixtures subjected to impact forces for the purpose of improving the impact resilience of concrete elements such as concrete traffic barriers and other applications. The first part of this study involved small-scale testing of preliminary mixtures to optimize compressive strength, modulus of rupture, and impact resilience using a fixed percentage of tire chip replacement of the coarse aggregate and varying volume fractions of steel, polypropylene, and polyvinyl alcohol fibers. Rubberized FRC beams were then tested under static loads to maximize the static energy dissipation potential of steel fiber inclusion at varying tensile steel reinforcement ratios. The final part of this study involved performing scaled drop-weight impact tests on reinforced concrete beam. Results confirmed that rubberized and/or fiber reinforced cementitious composite members exhibit significantly improved energy dissipation capacity and impact resilience, particularly with 1.0% steel fiber addition and 20% tire chip replacement. It was observed that more energy was dissipated through the steel fiber addition alone than FRC mixtures with the tire chips.

Keywords: cementitious composites, fiber reinforced concrete, FRC, rubberized concrete, energy dissipation, impact, macro fiber, steel fiber, recycled tire chip

Impact Resistance and Strength of SCC Containing Crumb and Powder Rubbers

Assem A. A. Hassan

Synopsis: The inclusion of rubber in concrete mixtures improved the impact resistance but negatively affected the strength and fresh properties of self-consolidating concrete (SCC). The objective of this investigation was to optimize the balance between the improved impact resistance and the reductions in the strength and fresh properties of rubberized SCC mixtures. This investigation evaluated and assessed the type/size and percentage of rubber needed to develop successful SCC mixtures with maximized impact strength and minimized reductions in strength. The studied variables were the type/size of rubber used (crumb rubber (CR) and two sizes of powder rubbers), percentage of rubber (0%, 15%, 25%, 30%, 35%, and 40%), type of concrete (SCC and vibrated concrete), and the use of fibers in the mixture. Because of the fresh properties restrictions of SCC, it was only possible to develop rubberized SCC with up to 25%, 30%, and 35% CR, powder rubber 40/80, and powder rubber 140, respectively. With the absence of fresh properties restrictions of SCC, it was possible to develop vibrated rubberized concrete with up to 40% of any type of rubber. Using higher percentages of rubber in vibrated rubberized concrete dropped the compressive strength to less than 25 MPa (3.63 ksi). The results also indicated that despite the slight improvement in the fresh properties and strength of mixtures with powder rubbers compared to mixtures with CR, mixtures with CR showed significantly higher improvements in the impact resistance.

Keywords: Impact strength; SCC; compressive strength; crumb rubber; powder rubber

Assessment of Material Flow during Projectile Penetration of Concrete Targets

Girum Urgessa and Robert Sobeski

Synopsis: This paper presents qualitative and quantitative assessment of material flow response during projectile penetration of concrete targets using outputs from the finite element analysis. The assessment included two parts. First, the movement of the comminuted concrete was analyzed by examining the normal expansion of meshless particles using NECM (Normal Expansion Comparison Methodology). Second, the expansion of finite element nodes adjacent to meshless particles was analyzed by observing direction cosines and velocity profiles of the nodes using SECM (Spherical Expansion Comparison Methodology). This assessment is important to re-examine simplified assumptions used in analytical penetration depth equations that were developed without providing adequate insight into material flow.

Keywords: projectile penetration, impact, finite element analyses, material flow, concrete targets

Hard and Soft Projectile Impact Simulation of Prestressed Concrete Panels

Seong Ryong Ahn and Thomas H.-K. Kang

Synopsis: Impact resistance of concrete panels has been researched since the 19th century. Studies therein primarily focused on conventionally reinforced concrete and steel fiber-reinforced concrete. Little research on the impact resistance of prestressed concrete exists. This paper investigated the impact resistance of prestressed concrete panels subject to hard and soft/hollow projectiles and under an assortment of prestressing levels. Damage mode, velocity change, impact force, and internal energy were measured and analyzed. A total of twelve finite element analyses, which considered high strain rate effects, were performed, as well as preliminary analyses with different mesh sizes. It is observed that level of prestressing tends to improve perforation resistance of concrete panels. Additionally, large deformation at soft projectiles occurred during impact, consuming the greater internal energy of the projectiles, unlike hard projectiles. As a result, soft projectiles caused a smaller degree of local failure on the concrete panels than hard projectiles with the same mass and velocity.

Keywords: impact resistance, finite element analysis, prestressed concrete, hard projectile, soft projectile.