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Replication studies paper

Dynamic identification of damage control characteristics of ultra-high performance fiber reinforced concrete

H. Othman *, H. Marzouk

Department of Civil Engineering, Ryerson University, Toronto, ON M5B 2M2, Canada

HIGHLIGHTS

- A thorough characterisation of the impact damage tolerance of UHP-FRC is presented.
- Superior damage control properties of UHP-FRC are addressed experimentally.
- Significant of increasing fiber volume content on controlling the damage in UHP-FRC is addressed.
- Random decrement technique is used to detect damage existence.

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ABSTRACT

An experimental investigation has been conducted to assess the damage control properties of ultra-high performance fiber reinforced concrete (UHP-FRC) in comparison to traditional concrete. Five identical reinforced concrete (RC) plates, with the exception of concrete material, are damaged gradually using repeated impact technique. Damage progression has been evaluated stepwise based on the change in dynamic parameters and validated by visual inspection, midpoint residual displacement and successive number of impact tests to each specimen. Test results showed that UHP-FRC exhibits superior damage characteristics. The damage rate of UHP-FRC materials are approximately in the range of 6–15% the damage rate of normal-strength concrete.

1. Introduction

UHP-FRC is a new class of concrete that has been developed to give a significantly higher material performance in comparison to its concrete counterparts. UHP-FRC exhibits superior mechanical characteristics, including a compressive strength of greater than 150 MPa, high elastic modulus, high elastic limit, tensile strength in the range of 8–15 MPa, strain hardening in tension [1], fracture energy of several orders of magnitudes of traditional concrete and high post-cracking capacity [2]. The ultra-high compressive strength of UHP-FRC is achieved by using optimum combination of very fine aggregates that ensure homogeneity and dense packing [3]. On the other hand, the enhancement in tensile/flexural, fracture energy, and damage control properties are mainly attributed to randomly disperse of discontinuous fibers and improvements to the fiber-matrix bond [2]. Further details regarding mechanical properties of UHP-FRC can be found in [3–6].

Several experimental material investigations have confirmed that UHP-FRC exhibits excellent dynamic and damage control properties [7–9]. Experimental investigations on the dynamic response and/or damage assessment of UHP-FRC structural members under dynamic loads are limited (e.g., [10–13]). In conclusion, all these experimental studies have demonstrated that UHP-FRC has superior damage control properties under dynamic loading conditions compared to other concrete classes. However, in all these investigations the damage characteristics of UHP-FRC have been assessed based mainly on visual inspection of specimens after testing. Additionally, there is no available data related to the damage rate monitoring of UHP-FRC structural members at different levels of damage.

Many structural applications may be subjected to subsequent accidental impacts during the operation lifetime, such as nuclear applications, offshore platforms, transportation structures, etc. Impact loading scenarios may create internal damage that may

* Corresponding author.
E-mail address: hesham.othman@ryerson.ca (H. Othman).

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be undetectable by visual inspection; however, it can cause severe reduction in the structure stiffness and integrity. Vibration based damage identification techniques (VBDIT) can be considered as one of the most popular structural health monitoring methodologies to detect the global structural damage [14]. VBDIT methods have achieved significant research interest in recent years, mainly due to their nondestructive nature and their ability to assess invisible damage. The basic concept of VBDIT is that structural damage or deterioration, which reflected in stiffness properties and mass distribution, cause detectable changes in the dynamic response of structures. VBDIT is based on this concept of monitoring the change in dynamic modal properties between the intact and damage state. Natural frequencies, damping values, and mode shapes are the most common modal properties extracted from vibration measurements. Theoretically, natural frequency is proportional to the square root of the stiffness; an increase in structural damage (i.e., lower stiffness) leads to a shift in the natural frequencies towards lower values. On the other hand, damping still remains the most uncertain modal parameter of structures dynamic response due to its intrinsic complexity [15]. In reality, structure deterioration creates an increase in the internal friction losses caused by relative motion of material particles [16]. Such increase in dissipated frictional energy, mainly as friction heat, is reflected in higher structural damping [15,16].

Recently, the natural frequency-based damage detection method has received much attention since the frequencies can be measured experimentally from few accessible locations. At the same time, it is simple to predict natural frequencies numerically using finite element (FE) simulations [14]. Numerous experimental studies using frequency-based damage indices have been used successfully to detect global damage in RC structures, such as pier walls [17], T-shaped beams [18] and rectangular beams [19–21]. The use of damping-based damage indices has not achieved much research interest in the literature. In addition, different conclusions have been drawn for the damage effect on the damping ratio. Some researchers have confirmed the increasing trend of damping factor with the severity of damage [17,20–22]. Others have indicated that the damping factor is not sensitive to the damage level [23–25]. A worth of mentioning here that the mode shapes of structural members do not change significantly with increasing the damage level [18].

In general, it is hard to obtain measurable free vibration decay for RC structural member because of its high stiffness and/or low excitation level. Additionally, the random nature of forced vibration tests does not satisfy the free-vibration assumption [26]. As a result, it is difficult to obtain reliable damping measurements as reported in [23–25]. In such cases, the random decrement (RD) technique can be used to extract the free decaying response of structural member. RD is a powerful numerical averaging technique that assumes the forces are zero-mean, stationary Gaussian random process [20,26]. RD is categorized as an output based method in which the structural free-vibration response is obtained from response measurements without knowledge of the excitation force. RD estimates dynamic parameters more accurate in comparison with the correlation function method [27]. Noise reduction is another advantage of RD technique [26]. Owing to its efficiency and simplicity in processing vibration data and the lack of requirements for input measurements, RD has been used extensively to detect damage in RC offshore structures (e.g., [26,28]). Most recently, RD has been used successfully by the co-author to detect damage in steel and RC beams using more sensitive fiber-optic sensors [20]. Details about the mathematical derivation, application, and limitation of RD technique are discussed in [20,26].

This study is part of ongoing research program by the authors aiming to develop high integrity UHP-FRC waste containers for low and intermediate level radioactive wastes. In general, waste containers may be subjected to accidental dynamic loading that may cause greater damage, such as drops or collisions, during waste transport and handling at the storage/disposal facility. This investigation is a stepping stone in order to address the advantage of using UHP-FRC in controlling the damage progression that may be caused by repeated accidental impacts. A second objective is to investigate the significant of increasing fiber volume content on controlling the damage progression in UHP-FRC material. Comparing the damage level associated with a prescribed loading technique of different materials, known as damage tolerance, is generally assessed through repeated impact testing techniques. ACI Committee 544 proposed a repeated drop-weight impact technique for evaluating the damage resistance of fiber concrete materials [29]. In which, a steel ball is dropped consecutively from a constant height onto the specimen and the number of impacts is the main parameter. Same procedures are followed in this study. Repeated impact tests with the same impact energy have been conducted to assess the damage progression of UHP-FRC in comparison with traditional normal- (NSC) and high-strength concrete (HSC). Forced vibration tests are performed at eight different damage levels during the drop-weight sequences to monitor the change in the modal parameters. The free-vibration response is obtained using RD technique. The measured natural frequencies of tested plates are estimated numerically using linear perturbation analysis available in ABAQUS [30] to verify the used RD technique. Damage progression rate is assessed stepwise based on visual inspection, successive number of impacts, residual displacement and the change in dynamic modal parameters.

2. Test specimens

Five RC plates with identical dimensions and steel reinforcement ratio are constructed and tested at the Structural Laboratory of Ryerson University. The plates are 1950 mm square with a thickness of 100 mm and 15 mm clear cover to reinforcement. All plates are doubly reinforced with equal top and bottom orthogonal steel reinforcement mats. Standard Canadian deformed steel bars 10M-CSA of Grade 400 with spacing of 100 mm are used as longitudinal reinforcement in all plates [31]. Two parameters are considered, namely: concrete class (NSC, HSC and UHP-FRC); and fiber volume content of UHP-FRC mixes (1, 2, and 3%). All plates are tested under same supporting conditions at their four corners. The supporting system has been designed to prevent the uplift of supports without creating any significant restraint moments. Typical dimensions, reinforcement layout, and supporting conditions of test specimens are shown in Fig. 1.

The NSC plate is cast using a ready-mix plain concrete with a nominal compressive strength of 35 MPa and 10 mm maximum aggregate size supplied by a local concrete company. The HSC plate is constructed using a plain HSC with a target compressive strength of 80 MPa. This mix is based on the composition developed and used previously in [32,33]. The UHP-FRC plates are cast using a commercially proprietary product [34]. The UHP-FRC mixes have identical mix proportions with the exception of fiber volume content. Straight steel fibers with different volume contents of 1, 2, and 3% are used in UHP-FRC mixes. These fibers have a diameter of 0.2 mm and are 13 mm long. This fiber geometry has an aspect ratio of 65, offering a trade-off between good workability and high pullout resistance [1,9]. It should be pointed out that, in this investigation, the used upper limit of 3% fiber content is based on workability results of preliminary small size mixes. Fiber content of more than 3% affected the flowability of fresh concrete significantly. Table 1 provides the mix proportions of concrete materials used throughout this investigation.