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Piezoresistive behavior of CF- and CNT-based reinforced concrete beams subjected to static flexural loading: Shear failure investigation

Gürkan Yıldırım [a,*], Mohammad Haroon Sarwary [b], Ali Al-Dahawi [c], Oğuzhan Öztürk [d], Özgür Anıl [b], Mustafa Şahmaran [e]

[a] Department of Civil Engineering, Adana Science and Technology University, Adana, Turkey
[b] Department of Civil Engineering, Gazi University, Ankara, Turkey
[c] Department of Building and Construction Engineering, University of Technology, Baghdad, Iraq
[d] Department of Civil Engineering, Selçuk University, Konya, Turkey
[e] Department of Civil Engineering, Hacettepe University, Ankara, Turkey

HIGHLIGHTS

- Self-sensing and structural behavior of reinforced concrete beams were assessed.
- CF and CNT were used to improve electrical properties.
- Self-sensing of shear damage under four-point bending was of particular focus.
- Structural behavior and failure mode of CF- and CNT-based beams were quite different.
- Damage in shear was successfully self-sensed with superior performance of CF.

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ABSTRACT

Self-sensing property of concrete is mostly assessed using small specimens without reinforcement, which may be misleading for real-time structures. To better simulate the actual field conditions, this study examined self-sensing of damage in large-scale reinforced concrete beams tested under four-point bending. During flexural testing, special attention was paid to the self-sensing capability of shear failure, since this type of failure occurs suddenly and catastrophically. Inadequate shear reinforcements were used to increase shear failure possibility of $100 \times 150 \times 1000$ mm^3 (width × height × length) reinforced large-scale beams and beams were produced with a high shear span (a = 350 mm) to effective depth (d = 125 mm) ratio of 2.8. To increase the electrical conductivity of large-scale beams, chopped carbon fibers (CF) and multi-walled carbon nano tubes (CNT) were used. Instantaneous self-sensing recordings were made using brass electrodes embedded in different shear spans of beams. In addition to conducting self-sensing evaluations, researchers also investigated the effects of CF and CNT particles on the mechanical properties/structural behavior of large-scale beam specimens with the proposed reinforcement configuration. Results showed that compared to CNT, CF usage significantly improved the load carrying capacity and ductility, resulting in bending mode of failure even with indaquate shear reinforcement. Shear damage was successfully self-sensed in all tested beams, although all CF-based specimens started self-sensing from the beginning of loading with significantly higher changes in electrical resistivity results, unlike CNT-based specimens. Conductive network of CF-based specimens seemed to be disturbed more easily at high load levels. CF usage seems like a better option compared to CNT given its lower cost and easier mixability.

1. Introduction

The built environment consists of large, complex and expensive structural systems. Although catastrophic failures can be prevented by following the structural design codes, infrastructures inevitably face damage while in operation. Structural

* Corresponding author.
E-mail address: gyildirim@adanabtu.edu.tr (G. Yıldırım).

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damage can occur due to extreme loads such as earthquakes, dimensional changes due to shrinkage and creep effects, mechanical loads, environmental loads from cyclic wetting/drying, freezing/thawing and temperature fluctuations, or a combination of those types of damage, with or without structural maintenance. To keep infrastructures in a serviceable state, it is important to identify and assess any structural damage as early as possible.

Structural health monitoring (SHM) systems can be used to determine the condition of structures rather than relying on visual inspections, which are subjective and labour-intensive. Generally, SHM systems use installed/embedded sensors. Data recordings are collected and analysed in a centralized data pool using a coaxial communication cable. However, using cables to transfer data recordings to the data pool results in high system costs and labour-intensive installations. For example, installating 10–15 sensors for small-scale systems can cost $5000 per sensor channel [1]. Larger systems such as long-span bridges require more sensors [2,3], which can be prohibitively expensive, especially if cables must be placed in weatherproof channels. Also, despite the availability of sensors and their usability for SHM purposes [4–6], most sensors are reported to be non-durable, overcosting, unavailable for continuous monitoring and incompatible with concrete structures [7]. To ensure widespread applications and sustainability, it is critical to overcome these drawbacks.

One potential solution is to make concrete itself a sensory material, enabling it to self-sense damage without compromising safety. Compared to other sensory components, self-sensing concrete materials can be manufactured at reasonable prices, using conductive materials to create a homogenous electrically conductive network within the concrete. Self-sensing concrete makes it possible to continuously monitor damage through observation of electrical properties (i.e. resistivity) [8–18]. To incorporate the capability of high electrical conductivity into conventional concrete for self-sensing purposes, electrically conductive materials (ECMs) such as nickel powder, carbon fibers/nanofibers, carbon nanotubes, graphene and carbon black are typically used. Studies focusing on the effects of ECM type on self-sensing [19,20], mixing method for ECMs in cementitious matrices [19,21,22], dosage of ECM [20,23–25] and overall moisture state of concrete material during testing [26–28] can be found in literature. Along with the abovementioned factors that influence self-sensing capability, the impact of embedded steel reinforcement was also studied by Wen and Chung [29]. This investigation showed that embedded reinforcing steel bars have a positive influence on the piezoresistive behavior of CF-reinforced cement-based composites under flexural loading. On the other hand, after an extensive literature review, the authors did not encounter any research into the self-sensing capability of large-scale structural steel-embedded beam elements tested under bending, and therefore attempted to fill this knowledge gap by simulating real-life cases more clearly.

Self-sensing of shear failure during flexural testing was a particular focus of this study, since this type of failure can be catastrophic. Researchers produced ($100 \times 150 \times 1000\ mm^3$ – width $\times$ height $\times$ length) reinforced large-scale beam components with chopped carbon fibers (CF – micron-size) or multi-walled carbon nano-tubes (CNT – nano-size) and tested them under four-point flexural loading. Carbon-based materials were selected based on the results of a recent study of the authors [19], which reported best performances from CF- and CNT-based cement-based materials out of other carbon-based materials. Mechanical properties and structural behavior of reinforced large-scale beams were also investigated.

2. Experimental program

2.1. Materials, proportioning and mixing

Mixture design for large-scale beam specimens included CEM I 42.5R ordinary Portland cement (PC), Class-F fly ash (FA) with CaO content of 9.78%, and fine silica sand with maximum aggregate size of 0.4 mm, specific gravity of 2.60 and water absorption capacity of 0.3%, drinkable water and policarboxylic ether-based high-range water reducing admixture (HRWRA). Chemical/physical properties and particle size distributions of conventional dry raw materials are shown in Table 1 and Fig. 1, respectively.

Micro-sized chopped carbon fibers (CF) which were obtained from ELG Carbon Fibre Ltd. with the brand name of Carbiso™ CT12 and nano-sized multi-walled carbon nano-tubes (CNT) which were obtained from Grafen Chemical Industries with the brand name of KNT-I13 were used to increase the electrical conductivity of specimens. CFs had a tensile strength of 4200 MPa, elastic modulus of 240 GPa, elongation of 1.8%, density of nearly 1.7–2.0 g/cm^3, 7.5 μm diameter and 12 mm length. CNTs were 20–30 nm in diameter, 10–30 μm in length, had a surface area of more than 200 m^2/g and purity greater than 90%. Fig. 2 shows photographs of CF and CNT particles taken under video camera and scanning electron microscope (SEM). To prevent air bubbles in mixtures with carbon-based materials, a foam remover in powder form was also used at 0.3% of total cementitious materials (PC + FA) in mixtures, by weight.

Water to cementitious materials (CM = PC + FA) ratio (W/CM) and fly ash to Portland cement ratio (FA/PC) were kept constant at 0.27 and 1.2, respectively. Utilization rates of different carbon-based materials were chosen based on the study authored by Al-Dahawi et al. [20]. Accordingly, CF and CNT utilization rates were set at 1% of total mixture volume and 0.55% of total weight of cementitious materials, respectively. These rates are the percolation thresholds, which are the minimum carbon-based conductive material contents over which sharp drops in electrical resistivity start to diminish. During the decision making of utilization rates and mixing methods (as will be detailed in the next paragraph) of different carbon-based materials, highest increments noted in the electrical conductivity (i.e. highest decrements in electrical resistivity) results of $Ø100 \times 80\ mm^2$ cylindrical mortar specimens were taken into account. Details regarding with the percolation thresholds and mixing methods of different carbon-based materials were throughly elaborated in the recent studies of the authors [19,20].

Keeping the HRWRA amount constant for cementitious systems incorporating carbon-based materials with relatively different properties (Fig. 2) was a challenge. Rather than using a fixed amount, mixtures were produced to achieve similar workability properties. To ensure these similarities in mixtures with CF and CNT, researchers performed mini slump flow tests, obtaining flow deformation levels with average mini slump diameter of approximately 16 cm from all mixtures. Details related to workability characteristics of different mixtures can be found in [19,20].

Because uniform distribution of different carbon-based materials within cementitious mixtures is crucial for a continuous electrically conductive network, different methods were used for mixing CF and CNT into cementitious matrices, as outlined by Al-Dahawi et al. [19]. CFs were first mixed with the dry raw materials (PC, FA and silica sand) in a 5-liter-capacity mortar mixer at 100 rpm for 10 min. After slowly adding the mixing water at 100 rpm over 10 s, speed was increased to 300 rpm, all of the HRWRA was added over 30 s, and mixing of all materials was continued for an additional 10 min at 300 rpm. On the other hand, CNTs were mixed with the entire amount of mixing water and HRWRA with a