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Detection and prediction of seismic damage to a high-strength concrete moment resisting frame structure

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ABSTRACT

This paper describes a unique research program on the behavior, damage prediction and detection of a full-size, two-storey, high-performance concrete building subjected to a series of earthquake excitations. Repeated pseudo-dynamic tests were carried out on the structure during which increasing seismic forces were applied, with resulting greater levels of permanent damage to the structure. In order to monitor the level of damage, forced-vibration tests were carried out after each pseudo-dynamic test and were used to track changes in the building's key dynamic properties. This combination of tests is applied for the first time on a full-size, high-strength concrete frame structure with recent seismic detailing. The paper presents the design of the test structure, the series of forced vibration and pseudo-dynamic tests, and the evaluation of building damage. To validate the procedure, identified stiffness reductions are related to quantities measured during pseudo-dynamic tests and to observed damage. A novel model updating procedure, including regularization, is applied to the structure and is shown to accurately predict the location of the increasing damage in the building.

1. Introduction

Damage detection and identification of civil structures is of great importance for safety and for the management and maintenance of these structures. Conventional methods such as visual inspection or acoustic methods have generally limited efficiency, because the location of the damages must be known a priori and all parts of a structure are not necessarily accessible. For these reasons, interest has grown in the past two decades for damage detection methods based on monitoring the changes of the dynamic properties of structures, because such methods allow for the measurement of the complete structure. Although different techniques have been applied successfully, most of them use simulated data [1] or simple laboratory specimens such as beams or plates or idealized down-scaled structures with artificially introduced damage [2,3]. Tests on real structures are rarely possible, and often do not lead to satisfactory results because of environmental and other uncontrollable effects [4,5].

Detailed literature reviews about methods based on changes of the dynamic properties can be found in references [6,7]. Several identification methods were applied experimentally with varying degrees of success to reinforced concrete specimens (often beams). Several of these methods are only based on the changes of the vibration frequencies of the specimens and are mentioned in a dedicated literature review by Salawu [8]. Such methods are generally direct and very effective procedures to detect the existence of damages [9,10], but they have limitations. Frequency changes in a structures due to damages can indeed be altered by temperature changes, or they can be insignificant if damages occur near nodes of the monitored modes, and in most of cases localization and quantification of damages are not possible because vibration frequencies are only global parameters. A few studies, however, provided methods that could conveniently localize cracked regions in RC beams, by using only frequency based indices [11,12]. A wider family of damage detection methods are rather based on modal shapes, because shapes include local information about the structure that allows for more practical localization and quantification of damages. Among these methods, the most widely used indices in the literature for damage detection in RC specimens are the MAC (Modal Assurance Criterion) and the CoMAC [13]; the modal curvature of shapes [14,15]; the flexibility matrix [14,4]; the flexural stiffness [16]; and the strain energy [17]. Finite element model updating is another popular damage detection method that uses both frequencies and mode shapes to calibrate chosen physical parameters of a numerical structure [18]. This

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method is the one applied in this paper. A few studies of model updating methods with experimental data on RC structures lead to satisfactory results, but most of them are limited to small structural elements [19,20] and they often minimize the number of calibration parameters through modelization of the supposed damage [21,16]. Only a few applications of these methods on real structures can be found in literature and they concern only bridges with artificially imposed damages [22]. Model updating methods applied on full-scale buildings are rare and most of them concern only numerical model calibration, without damage detection studies [23]. A seismic damage detection study was carried out on a full-scale laboratory composite structure with steel columns and concrete slabs, using model updating, as reported in reference [24].

In this paper, a large-scale seismic testing project was conducted on a full-scale, two-storey, reinforced high-strength-concrete (HSC) moment resisting frame building. The building was subjected to repeated pseudo-dynamic and forced vibration tests as part of a research project on the seismic behavior of HSC structures and on damage prediction and detection. The main objectives of the tests were to evaluate the damage and performance under increasing seismic forces applied with pseudo-dynamic testing techniques and to provide experimental data from forced-vibration tests for predicting damage under increasing seismic loads. Objectives related to the use of high strength concrete in seismic design can be found in Mousseau and Paultre [25] and to modeling the seismic response can be found in Mousseau et al. [26].

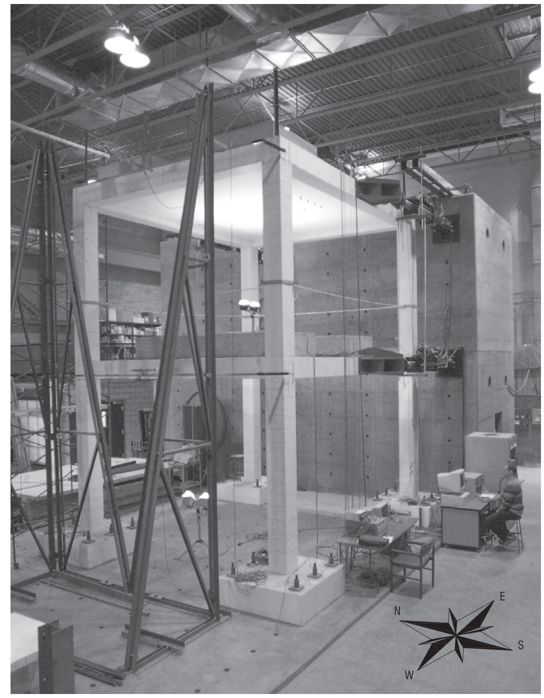

Fig. 1. Two-storey reinforced high-performance strength-concrete building with reaction wall.

2. Experimental program

The pseudo-dynamic technique was used to simulate increasing earthquake loading on the structure. The input ground motion recording was scaled to five different intensities and successively applied to the building specimen to inflict increasing level of damage. Forced-vibration tests were carried out between each application of the simulated earthquake loadings to obtain vibration frequencies, mode shapes and modal damping ratios using an eccentric-mass shaker mounted on top of the building. The initial forced-vibration tests results were used to calibrate the numerical model for the pseudo-dynamic testing method. This technique requires the development of a precise numerical model for the structure. Finally, parameterized models were updated with the dynamic properties at each step of increasing loading to detect stiffness reduction in members and identify damages to the structure.

3. Full scale two-storey HSC building specimen

The two-storey reinforced-high-strength concrete building shown in Fig. 1 has a 5-m bay in the E–W direction and a 4-m bay in the N–S direction. The storey height from top of slab to top of slab is 3 m. The building was designed in accordance with the *National Building Code of Canada* (NBCC) for a moment resisting frame with moderate ductility located in Montreal (Canada). Typical office building live loads of 2.40 kN/m^2 were used and the snow load was estimated at 2.32 kN/m^2. A superimposed dead load of 1.70 kN/m^2 – corresponding to mechanical services, floor finishing and partition loading – was used for the first floor, while a superimposed dead load of 2.10 kN/m^2 was used for the roof to account for mechanical services and insulation weight. Plan and elevation views of the building are shown in Fig. 2.

Fig. 3 shows the seismic base shear per unit seismic weight of the building (V/W) as a function of the fundamental lateral period of vibration for moment-resisting frames with moderate ductility built in Montreal according to 2005 NBCC provisions [27]. Fundamental period of vibration values of 0.2875 s and 0.4313 s were obtained using the simplified code equation and a finite element model, respectively, and are shown in Fig. 3.

Design and detailing of the structural members were in agreement with the special provisions for seismic design of CSA A23.3-94 *Design of Concrete Structures* [28]. The columns were all 300×300 mm. The two-way slab floor system consisted of a 150-mm-thick slab supported by beams 300×300 mm on all four sides. The specified concrete strength was 70 MPa and the specified steel yield strength was 400 MPa. Reinforcement details for the beams, columns and footing are illustrated in Fig. 4. More details can be found in Mousseau and Paultre [25].

4. Inducing seismic damage by pseudo-dynamic tests

Damage was induced by repeated simulated earthquake loading using the pseudo-dynamic testing (PSD) method [29,30,25]. PSD tests essentially require the same equipment as conventional quasi-static tests, in which prescribed histories of load or displacement are imposed on specimen structures by means of displacement-controlled hydraulic actuators. In this project, the lateral seismic loads were applied to the building by four 500-kN dynamic-rated servo-hydraulic actuators reacting on a reaction wall (Fig. 1). Two actuators were attached at mid-span of the slabs and spandrel beams running in the E–W direction at each floor level. The imposed displacements were measured with respect to two independent triangular steel trusses which can be seen in the foreground of Fig. 1 using displacement transducers. The two-storey building was fully instrumented with strain gauges to measure the deformations in the longitudinal reinforcement in the beams, columns, and slabs as well as in the transverse reinforcement in the columns and beams.

The lateral stiffness matrix used for the PSD test is a full 2-by-2 matrix corresponding to a system with two degrees of freedom, one at each floor level. The initial-state stiffness matrix for the