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Experimental response of an existing RC bridge with smooth bars and preliminary numerical simulations

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ABSTRACT

The paper discusses the experimental seismic performance assessment of a structural prototype simulating typical existing highway bridges which were designed with poor seismic details. The structural system is a reinforced concrete (RC) 1:3 scale single span bridge which has been tested dynamically with shaking tables by considering strong motions of the 1980 Irpinia (Italy) earthquake. Low-strength concrete and smooth bars were used for the RC circular bridge piers of the tested prototype. Comprehensive modal response analysis has been carried out for the single piers and for the bridge sub-assemblage to estimate period elongations and variations of equivalent viscous damping coefficients at increasing levels of strong motions. The effects of cumulative damage induced by earthquake sequences have also been investigated experimentally. The sample bridge pier possesses low aspect ratio; nevertheless the piers exhibited a flexural response. Fixed-end rotations, with significant longitudinal reinforcement slip, were observed at the base of the bridge pier at about 0.40% lateral drift ratio. As a consequence, a rocking mechanism of the bridge pier initiated; such mechanism affected significantly the pier response at large shaking intensities. An in-depth analysis of local and global response quantities has been provided in order to accurately identify the structural behaviour. Finally, available analytical formulations and refined numerical models were considered to simulate the earthquake response of the tested bridge. The pier lateral response has been investigated by means of push-over analysis and nonlinear time histories. The accuracy of the proposed models, the differences and recommendations for numerical modelling of bridge piers with smooth internal reinforcements are also discussed.

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1. Introduction

Most of the existing highway bridges, especially those with reinforced concrete (RC) structural systems, were built during the 60s and 70s and were designed for moderate seismic loads and with inadequate reinforcement details (e.g. [1–3] among many others). Due to the generally conservative bridge design, such systems possess moderate seismic vulnerability, especially at collapse, as surveyed in the aftermath of the past moderate-to-high magnitude earthquakes. Conversely, the occurrence of widespread structural damage, may pose a relevant threat for the regular traffic flow [3]. The screening of the Italian bridge stock shows that existing bridges are commonly characterized by single piers (5–10 m tall) simply supporting the bridge deck [e.g. 3]. The box-type is the most common cross-sections, but solid circular piers are also abundant.

Numerous post-earthquake reconnaissance surveys have shown that brittle failure due to either low shear capacity or inappropriate location of lap splices in pier members, flexural failure of piers with corresponding bar buckling and stirrup opening and/or ruptures are common damage patterns experienced by existing RC bridges with circular piers employing poor seismic details. In circular piers with intermediate-to-low shear span ratios, the most common failure is caused by insufficient anchorage or lap splicing, as also found experimentally in large scale tests (e.g. [4]). Such a damage pattern tends to be exacerbated for RC bridges employing smooth steel reinforcement bars and low-strength concrete. To date, the available experimental data for the investigation of the above damage mechanisms have been derived primarily from static or pseudo-dynamic tests carried out on single piers or sub-assemblies [5–8]. Component tests have provided essential data at the microscopic level [9]. However, such investigations do not account for number and amplitudes of cycles, strain rate effects that characterize earthquake loadings. Thus, there is an urgent need to further assess the seismic performance of existing RC

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highway bridges designed without seismic details. Emphasis should be on the reliable evaluation of the global dynamic behaviour and the influence of support conditions on system response, which, in turn, require the testing of a bridge as a whole.

Shake tables have been found highly effective for studies carried out world-wide in the last decade on RC new bridges sub-systems ([10–13], among many others). Available shaking table tests focused on the seismic response assessment of modern bridge systems or sub-systems, i.e. those employing adequate seismic detailing, capacity-designed bridges, or bridge components with small size specimens. They did not use smooth steel reinforcement bars and low-strength concrete for the RC piers. The influence of the latter design variables on the static response of RC columns has been extensively investigated [e.g. 5–8, among others], nonetheless, dynamic tests, e.g. shaking table tests, either on typical bridge piers or systems built in the Mediterrean earthquake prone regions are still lacking. Towards this aim, a recent comprehensive research program was carried out in the laboratory of the Department of Structures for Engineering and Architecture of University of Naples, Federico II, Italy. Such program deals with the structural response analysis of as-built and retrofitted RC bridge sub-systems. The project includes a series of more than 300 shaking table tests on 1:3 scale single span bridge representing typical existing highway bridges that were built during the 60s and 70s in the southern Europe, i.e. with smooth bars, low-resistance concrete, poor seismic detailing and different support conditions.

The present paper focuses on:

- The outcomes of the shake table tests carried out on the simply supported existing bridge prototype subjected to the strong motions of the 1980 Irpinia (Italy) earthquake. 14 earthquake time histories (TH) and 26 white noise excitations were performed on the single pier and on the bridge prototype in the as-built configuration;
- The influence of smooth steel reinforcement and low-strength concrete on the seismic pier behaviour, both at local and global levels;
- The effects of the accumulation of damage induced by earthquake sequences on the RC circular piers of the bridge;
- Advantages and limitations of available analytical and numerical models accounting for the lack of concrete-to-steel bond are outlined. This allows the reader to quantify the differences with classical analytical approaches based on the perfect-bond and the needs for more accurate numerical modelling.

2. Case study

The bridge layout used as reference structure for the tested subassemblage comprises an existing RC multi-span simply supported bridge system, with two highway traffic lanes (total width of 7 m) and 22.65 m long girders. The deck consists of three RC prestressed precast 1.25 m high I-beams with 0.25 m thick solid deck. The deck is simply supported to represent typical configurations of existing RC bridges systems in the Italian highway network (e.g. [3,14] among many others). Pier geometry and reinforcement details are compliant with guidelines and design standards used in Italy during the 60s [1–3]. It is assumed that the reference multi-span simply supported RC highway bridge is located close to the city of Avellino, in South of Italy, in the Apennine Chain, where historical faults have been identified (region with moderate-to-high seismic hazard). Such faults generated the devastating 23rd November 1980 (M_S = 6.9) earthquake, also known as Irpinia earthquake, which was characterized by three distinct sub-events (i.e. earthquake sequence) occurring within the 40 s, along different faults, as further discussed in Section 4. The selection of the Irpinia earthquake swarm allowed the evaluation of the effects of the cumulative structural damage on the tested bridge system.

2.1. Prototype system

The dynamic tests on the sample bridge model were carried out by means of the earthquake simulator in the laboratory of Structures for Engineering and Architecture, Department of University of Naples Federico II, Italy. The earthquake simulator consists of two 3 m $\times$ 3 m square shake tables. Each table has two degrees of freedom along the two horizontal directions. The maximum payload of each shake table is 200 kN with a frequency ranging between 0 and 50 Hz, maximum acceleration equal to 1 g, maximum velocity equal 1 m/s and a total displacement equal to 500 mm (±250 mm).

For this study a scale factor of 1:3 for the member length was used to reduce the total mass of the system. The peak ground accelerations (PGAs) were not scaled. Such an approach is also applicable to the elastic moduli which cannot be easily modified in the structural materials. For dynamic systems, once the scaling factors of 3 independent parameters are fixed, other properties of the system can be calculated from dimensional analysis [15]. The use of both Cauchy and Freud similitude laws simultaneously, resulted in a set of scaling factors commonly adopted for shaking table tests [15,16]. The time of the input ground motions has been scaled by 0.57 ($1/\sqrt{3}$ according to similitude laws). Furthermore, a significant reduction of the prototype mass to 28 tons, 14 tons on each table, i.e. about 1/9 of reference full-scale bridge, was used. This scaling factor, derived by assuming the Freud number equal to the Cauchy number and the same density of mass between the bridge and scaled prototype, is 3 times higher than the scaling factor considering the scaled geometry (1/27). This resulted in the allocation of additional mass on the bridge deck to simulate realistic dynamic forces on the piers.

The use of a small scaling factor for member length led structural member dimensions and material properties compatible with those adopted in the formulations and calibrations of analytical models for global member capacity. To reproduce realistic bond forces, both interior reinforcements and concrete aggregate were scaled considering the product availability and mechanical characteristics. The use of micro-concrete was not considered to prevent significant modifications in the material properties. Longitudinal reinforcement bars with 10 mm in diameter and maximum aggregate size of 13 mm were used in the prototype construction, as commonly found in available bond characterization tests [6,17].

The scaled prototype is a 7.55 m (22.65 m full scale) span bridge, consisting of two piers and a simply supported bridge deck, as depicted in Fig. 1. The deck supports consist of a steel cylindrical hinge (pinned condition) and a Polytetrafluoroethylene (PTFE) Teflon-steel slider (roller). The coefficient of friction of PTFE materials on stainless steel plates is dependent on many variables, including pressure, sliding velocity and temperature. For the case study a 1.0% friction is assumed, as derived from ad-hoc characterization tests of the manufacturer. The bridge deck, which has a total mass of about 15.40 tons, was primarily utilized to simulate the inertial forces during the shake table tests. The total pier height is about 1.80 m (5.4 m full scale), with a cross-section diameter of 0.60 m (1.8 m full scale). Further details on the prototype dimensions are provided in Fig. 1. The bridge piers with a circular cross section have been designed according to typical 60–70s Italian practice [1]. Smooth bars, Aq 50 grade, were used for longitudinal and transverse steel reinforcements. For the RC piers, 25 longitudinal 10 mm-diameter bars anchored with end-hooks and a continuous spiral 6 mm diameter, 100 mm spaced, were used for the longitudinal and transverse reinforcements, respectively. Mechanical properties of steel bars were determined by means of tensile

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