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Cyclic response of I-shaped bridge columns with substandard transverse reinforcement

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ABSTRACT

The cyclic response of a typical bridge column with I-shaped cross-section and substandard transverse reinforcement was investigated by means of experimental and analytical research. The amount of transverse reinforcement was sufficient to ensure adequate shear strength, but other requirements of the Eurocode 8/2 standard related to the confinement and buckling of the longitudinal bars were not fulfilled. Failure was brittle due to the buckling and rupture of the longitudinal bars, which caused a progressive reduction of strength. The results of the experiment showed that the requirements of Eurocode 8/2 (which are quite stringent) related to the minimum volumetric ratio and the maximum centre-to-centre distance of the stirrups along the column, as well as the maximum distance between the engaged longitudinal bars, are justified in the investigated case. It was demonstrated that improperly designed stirrup hooks can cause a significant reduction in the ductility capacity of the column.

An attempt was made to strengthen the column using CFRP sheets. The strengthening was not straightforward. Two types of anchoring were investigated. The most efficient method of anchoring was based on the use of bolted steel plates. Due to the unfavorable dimension ratio of the column cross-section, the efficiency of the strengthening was limited.

The results of the experiment were used in order to identify the most suitable numerical models. Two engineering numerical macro models were analysed: a fibre based beam with hinges model, and a Giberson's model. In both cases agreement with the results of the experiment was fairly good, as long as the buckling of the flexural reinforcement was not pronounced, and substantial in-cycle strength degradation was consequently obtained. Some of the parameters (e.g. the ultimate deformation of the concrete in non-strengthened column) were calibrated according to the experiment, since the available models, reported in the literature, did not suit the investigated case. These parameters require further investigation.

The methods included in Eurocode 8/3, which are used to estimate the properties of the strengthened column, were compared. The procedures for estimation of the ultimate deformation capacity were also compared with some methods proposed in the literature. In the investigated case the best simulation of the experiment was obtained when the Lam and Teng's model of confined concrete was taken into account, together with a standard theoretical procedure for the estimation of the maximum chord rotation.

1. Introduction

In general, columns are crucial structural elements for the seismic response of bridge structures. During the design, the seismic load is typically reduced. Therefore, the response of the columns should be ductile. Such behaviour can be achieved if there is a sufficient amount of properly designed lateral reinforcement. The task of this reinforcement is to prevent three types of brittle failure: shear failure, failure due to insufficient confinement of the concrete core, and failure due to buckling of the longitudinal reinforcement. All these phenomena are addressed in the currently valid standards, such as Eurocode 8/2 (EC8/2) [1]. Despite the existence of adequate provisions in these standards, in many bridge structures (including new structures) the lateral reinforcement of columns has been typically designed for the prevention of shear failure only. The other two above-mentioned types of failure are often inadequately considered or even neglected. This can be of

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particularly importance in the case of columns which have an unfavourable shape in cross-section.

Typical examples are columns with I-shape cross-sections, which are commonly used in central Europe. Their seismic response can be especially critical in their weak direction, considering that the ratio between the available flexural capacity of the columns and the seismic demand is typically much more unfavourable than in the transverse direction. For example, in the typical bridge, presented in Fig. 1, the seismic demand of the central columns is almost the same in both horizontal directions, whereas their flexural strength is about three times larger in the transverse (strong) direction. In many similar bridges an essentially elastic response in the transverse direction can be expected.

Due to the relatively large seismic demand in the longitudinal direction (i.e. the weak direction of the columns) a large amount of lateral reinforcement is needed in order to provide an adequate ductility capacity. The large dimensions and complex shapes of the cross-sections of bridge columns (compared to columns which are typical for buildings) make the design of transverse reinforcement particularly complex.

A typical bridge structure supported by I-shaped columns is presented in Fig. 1. In this particular example the shear reinforcement was designed taking into account the requirements of EC8/2. However, the transverse reinforcement does not meet the provisions of EC8/2 related to buckling of the longitudinal bars (see the details given in Section 6.2.2 of EC8/2) and confinement of the concrete core (see the details given in Section 6.2.1 of EC8/2). The centre-to-centre distances between the hoops (see Eq. (6.9) of EC8/2), as well as between the engaged longitudinal bars (see the details given in Section 6.2.1.2(2)P of EC8/2), are larger than the maximum values permitted by standard. The hoops are not properly constructed. No hooks are provided. They are only overlapped along the edges perpendicular to the weak direction of the column, which additionally increases the proneness to the buckling of the longitudinal reinforcement.

The ¼ scaled typical I-shaped column (hereinafter referred as "non-strengthened column") which includes all deficiencies, described above, was experimentally investigated in its weak direction. The cyclic test was performed. The description of the experiment and the main results are presented in Sections 2.1 and 2.2, respectively. The main purpose of this research was to define column's displacement ductility capacity and to test if the provided transverse reinforcement can prevent the buckling of the longitudinal bars and appropriately confine the concrete core in spite of the substandard details (note that the investigated viaducts are situated in moderate seismicity regions).

An attempt was also made to strengthen such a column. While a variety of different approaches for the strengthening of circular [2], rectangular [3], hollow-box [4,5] or diamond-shaped [6] bridge columns are available, there was hardly any mention of the strengthening of I-shaped columns, in the literature. Thus the strengthening was not straightforward. The new typical ¼ scaled I-shaped column was jacketed using carbon-fibre-reinforced-polymer (i.e. CFRP) sheets anchored to the column by means of steel bolted plates (hereinafter referred to as the "strengthened column"). The previously undamaged strengthened column was tested experimentally in its weak direction. The experiment is described in Section 3.1. The main results are presented in Section 3.2.

The experimental studies were used to calibrate the numerical models of the typical non-strengthened and strengthened columns. The capabilities of two lumped plasticity macro models of columns were analysed: (a) a fibre based beam with hinges model (hereinafter referred as "BWH model"), and (b) a Giberson's model. The results of this analysis are presented in Section 4. First the basic assumptions and the input data for the fibre based model are presented in Section 4.1.1. The comparison between analytical response, calculated using the BWH model, and the measured response is provided in Section 4.1.2. Both the ¼ scaled typical I-shaped column and strengthened column were addressed. The analysis using the Giberson's model is presented in Section 4.2. The latter content describes the basic assumption and input data for this model. The comparison with the experiment for both tested columns was analysed.

Fig. 1. Example of a viaduct supported by I-shaped columns.

2. Experimental investigation of the non-strengthened column

2.1. Description of the experiment

A typical ¼ scaled I-shaped bridge column (the non-strengthened column), as presented in Fig. 2, was tested. The column was fixed to the laboratory floor by means of four steel rods. The cyclic test was performed under a constant axial load, which was maintained by means of two hydraulic jacks acting on each side of the column flange (Fig. 2a). The horizontal hydraulic actuator was used to gradually increase the displacement demand at the height of the 2.5 m in the weak direction of the specimen (corresponding to a height of 10 m in the as-built column). Three full cycles of the same displacement amplitude were applied (see Fig. 2b). The specimen was instrumented with strain gauges that were fixed to the lateral and longitudinal reinforcement. LVDT's were positioned along each side of the flanges of column's weak axis in order to measure the deformations.

The non-strengthened bridge column was designed based on the study of typical bridges supported by such columns [7]. It was revealed that, in the majority of cases, the normalized axial compression forces was typically within the range of between 8% and 11% of the characteristic compression strength of the concrete. At such a level of the axial force special lateral reinforcement, which ensures appropriate confinement and prevents buckling of the longitudinal bars, is needed [1].

The main deficiencies of typical as-built (full scale) columns are: an insufficient amount of transverse reinforcement, the distance between the hoops being greater than the maximum permitted value in EC8/2 (see Section 6.2.2(2)), the centre-to-centre distance of the engaged bars exceeding the maximum distance prescribed in EC8/2 (see Section 6.2.1.2(2)P), and the hoops being improperly designed, without properly shaped hooks (see Fig. 3 for details).

The cross-section area A and moment of inertia around the weak axis I of the non-strengthened column were, respectively, $A = 0.328\ m^2$ and $I = 0.0047\ m^4$ ($A = 5.25\ m^2$ and $I = 1.20\ m^4$ in the as-built column). The level of the normalized axial force $\nu = 0.11$ and the ratio of the longitudinal reinforcement $\rho_l = 0.8\%$ was the