Structures 15 (2018) 115–130

Contents lists available at ScienceDirect

Structures

journal homepage: www.elsevier.com/locate/structures

Seismic Structural Assessment of the Christchurch Catholic Basilica, New Zealand

Luís C. Silva[a,*], Nuno Mendes[a], Paulo B. Lourenço[a], Jason Ingham[b]

[a] ISISE, Department of Civil Engineering, University of Minho, Azurém, 4800-058 Guimarães, Portugal
[b] Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand

ARTICLE INFO

Keywords:
Basilica
Christchurch
Seismic assessment
FE modelling
Pushover analysis

ABSTRACT

An evaluation of the seismic performance of the Christchurch Catholic Basilica, New Zealand, also known as the Cathedral of the Blessed Sacrament, is presented. The cultural importance of the Basilica has been recognised, as it is listed as a Category I building on the New Zealand heritage register. Four strong earthquakes that occurred between September 2010 and June 2011 caused progressive damage and local collapse in the Basilica. Numerical analyses were performed to allow a seismic assessment of the Basilica using the Finite Element Method. A macro-modelling approach following homogenization concepts was considered and the seismic behaviour of the structure was evaluated through pushover analysis with the distribution of forces being proportional to the mass. The analyses allowed damage patterns and capacity curves to be determined, and identified the most vulnerable elements, the maximum load capacity, and the expected collapse mechanisms. Furthermore, a comparison between the numerical output and the existing crack patterns was undertaken, and good agreement was obtained. Finally, two strengthening techniques were evaluated with the aim of reducing the seismic vulnerability of the structure by avoiding collapse of the most vulnerable structural elements.

1. Introduction

Cultural heritage buildings include structures that represent a set of particular values that symbolically allow them to become part of a given identity and continuity [1]. Nowadays, the conservation principles and recommendations of the international council on monuments and sites (hereafter, ICOMOS) [2] aim to guarantee that the identity and significance of heritage buildings will be safeguarded. These guidelines are the outcome of centuries of ideological evolution, including aesthetic and technical issues [3,4].

Presented herein is an assessment of the seismic performance of the Cathedral of the Blessed Sacrament, also known as the Christchurch Catholic Basilica. The Basilica is listed as a Category I building on the New Zealand (NZ) heritage register ("*special or outstanding historical or cultural significance or value*") [5] and was subject to a strengthening intervention in 2004. Its safety level was assumed to be adequate then, but, a sequence of earthquakes caused progressive damage and local collapses. Four main seismic events occurring over a period of nine months were identified, being: (i) on the 4 September 2010; (ii) on the 26 December 2010; (iii) on the 22 February 2011; and (iv) on the 13 June 2011. Recognising the symbolism and type of loss associated with this Basilica, the presented study aimed to represent a contribution to the conservation and restoration of cultural heritage buildings, enrich the literature in the field and demonstrate the capability of current advanced analysis tools for engineering applications.

The scope of the research is particularly relevant if one notes that the lack of prompt action has been indicated as the main cause of collapse of important cultural heritage buildings, for instance St Marco's Campanile in Venice (Italy) in 1902, the Civic Tower of Pavia (Italy) in 1989, and St Martinus Church in Kerksken (Belgium) in 1990 [6]. It is known that existing UnReinforced Masonry (URM) buildings present a high seismic vulnerability [7]. This vulnerability can be attributed to: (i) poor out-of-plane capacity, which is directly associated with the low tensile strength of URM; (ii) a lack of capacity to dissipate energy; (iii) the absence of seismic requirements at the time of construction [7,8]; (iv) a lack of proper connections between structural elements [9]; (v) flexibility of the floors [10]; and (vi) deterioration of materials over time [11].

The process of intervention in these constructions is complex due to the lack of structural information and their high importance. A scientifically based intervention is less susceptible to inadequate actions and thus, in order to avoid damaging measures, the adopted methodology should be incremental, including studies such as an historical literature review, inspections, monitoring actions, and structural analysis

* Corresponding author.
E-mail addresses: id5563@alunos.uminho.pt (L.C. Silva), nunomendes@civil.uminho.pt (N. Mendes), pbl@civil.uminho.pt (P.B. Lourenço), j.ingham@auckland.ac.nz (J. Ingham).

https://doi.org/10.1016/j.istruc.2018.06.004
Received 10 August 2017; Received in revised form 4 April 2018; Accepted 15 June 2018
Available online 19 June 2018
2352-0124/

[12,13]. In this way, an intervention should be carried out after a careful diagnosis and evaluation of the safety of the structure in its present state, as defined in the ICOMOS principles [14]. In the evaluation of safety, numerical modelling is a valuable contribution to assess the structural behaviour of historical buildings.

There are several approaches and types of analysis that can be used to evaluate the behaviour of masonry structures. The differences are mainly related to assumptions about the material and structural behaviour, number of input parameters, modelling effort, computational time required, and post-processing results. Rational approaches correspond to easy-to-use and fast solution methods. Nevertheless, the use of graphic methods has become outdated due to computer technology [15] and the analysis of historical construction using thrust-line methods is difficult to apply in buildings with very complex geometries. However, static approaches based on thrust-lines and limit analysis [16,17] are a useful tool to estimate the load capacity of structures and are still used nowadays.

Limit analysis based on the kinematic approach is also a very practical and effective tool that requires few material parameters, which is a relevant aspect for historical structures due to the difficulty of obtaining the material properties [18]. Indeed, macro-block approaches, based on the rocking of monolithic walls, allow the collapse load factor of structures to be estimated [19–22]. However, an expert-based decision approach is required for each study case in order to correctly ascertain the potential collapse mechanisms [22]. Advanced finite element (FE) analysis makes it possible to easily combine modelling strategies and material constitutive models. In fact, the classic FE models, usually prepared based on micro-modelling and macro-modelling approaches, provide accurate results [23,24]. In the micro-modelling approaches, all the masonry components (units, mortar, and unit/mortar interface) are separately discretized, leading to models with a larger number of degrees of freedom and consequently a need for high computational efforts [25,26]. Macro-modelling considers masonry as a continuum and homogeneous material in which isotropic or anisotropic behaviour can be adopted [27]. This modelling approach has been used with success in the analysis of large masonry structures, as shown in [28–30], and is assumed here.

The outline of the paper is described next. First, a brief description related to the location, the main structural features of the Cathedral, and preparation of the FE numerical model is presented. The FE model was prepared using the software DIANA [31], assuming that the masonry is a continuous and homogeneous material (macro-modelling). Pushover analysis with a horizontal load distribution proportional to the mass was adopted to evaluate the seismic response of the structure. In the comparison between the numerical and real behaviour, the damage pattern, collapse mechanisms, and maximum load capacity were adopted.

Finally, two strengthening interventions are evaluated, aiming at avoiding local collapses and taking into account the requirements (ultimate limit state) defined in the seismic code of NZ (NZS 1170 [32]).

2. Cathedral of the Blessed Sacrament

2.1. Description of the structure

The Cathedral of the Blessed Sacrament (see Fig. 1) was designed by the architect Francis William Petre. The Cathedral is based on Roman style, in which the typical features of the arrangement, that is, a nave, a transept, chapels, an apse, a dome, and bell towers are presented. The Basilica was built in only four years, between 1901 and 1905, using Oamaru limestone. The Basilica has, in plan, a length of 62 m (north and south directions) and a width of 27 m (west and east directions). The highest element is the dome, with a height of 36 m, followed by the two bell towers, which are 32 m in height (see Fig. 2). The walls were built with two-leaf stone masonry and a concrete core in the middle. The stones are linked through grout-filled cavities and have a thickness of about 50 cm. The internal and external claddings have a thickness of 12.5 cm of limestone [33]. The thickness of the concrete core is equal to 20 cm. The domes are copper lined and the main dome is supported by four large arches, made from no-fines concrete, that spring from four large piers at the first-floor level with an internal spiral above [33]. The main dome is located above the sanctuary, which is not a common feature of this type of church: usually, the main dome is located at the crossing of the transepts and nave. The nave contains colonnades with diverse capitals and spacious arcades.

In order to assure an appropriate seismic behaviour, a structural study was performed in 2002, adopting simplified analyses and practical engineering judgement [33]. Based on this study, a strengthening intervention was carried out, which involved: (i) new reinforced concrete (RC) slabs with a thickness of 10 cm at the first-floor and roof levels, aiming at providing a box-behaviour with rigid diaphragms; (ii) steel ties with a diameter of 3.2 cm and RC ring-beams with a cross section of $20 \times 60\,cm^2$ at the two bell towers, above and below the window openings; (iii) RC ring beams with sections of $20 \times 60\,cm^2$ at the top of the main dome, above and below the windows; (iv) post-tensioning at alternate columns of the nave colonnade; (v) grouting of external parapets and ornaments; and (vi) attachment of the gable ends of the roof, the transepts, and ornaments [33]. The adopted techniques focused on the weakest elements of the building. The building response was improved to reach the required standard values for lateral load capacity with a Peak Ground Acceleration (PGA) equal to 0.05*g* (*g* is the gravitational acceleration) [33]. An intervention based on empirical methods increased the lateral strength for a value of about 45% of the strength required by the code, which represents 33% of the required value defined by the current code [33]. It is noted that the intervention was designed based on the code NZS 1170 [32].

2.2. Damage survey

The description of the observed damage is presented below for each seismic event considered. It is important to note that as part of the Christchurch array of seismic recording stations, the accelerometer station designated as CCCC [34] was located only 20 m from the Basilica. This fact, which is not very common, allowed meaningful conclusions to be drawn about both the registered PGA and the accelerogram acting at the base of the Basilica structure. Nevertheless, some attention is required when comparing the recorded ground motions at the site against the demands specified by current seismic design standards [32], because the design spectra values can be biased if soil-structure interaction influences the ground motion characteristics, mainly in the range of long period, as reported in [35] for the studied series of earthquakes.

The first earthquake occurred in the early morning of 4 September 2010 with a moment magnitude of M_W 7.1. The epicentre was located near Darfield town, a region of Canterbury located 40 km west of Christchurch [36,37]. The peak geometric mean horizontal ground motion acceleration (PGA) registered at the CCCC station was equal to 0.22*g* [38], with the peak vertical PGA component being 0.15*g* [38]. The earthquake caused some damage to the Christchurch Catholic Basilica [33]. The walls were affected by minor cracking as well as significant movements in the stones of the west sacristy wall and out-of-plane movements in the middle column of the north bell tower (eastern elevation). Despite that, cracks were also observed in retrofitted elements, such as the underside of the first-floor diaphragm all around the nave and the main dome, in the form of shear cracks at the joints [33,39]. After the visual survey, the building was tagged with a red placard, which prohibited its usage [40].

The earthquake of 22 February 2011 presented a moment magnitude of M_W 6.3. The horizontal geometric mean PGA at the CCCC station was equal to 0.43*g* [41] and the PGA of the vertical component was 0.69*g*. This vertical component of the recorded ground motion was very significant when compared with the observed value for the September