An Extensive Survey of the Historic Center of Cusco for Its Seismic Vulnerability Assessment

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Abstract. This paper presents the main important typological data collected during an extensive survey carried out on the buildings of the historic center of Cusco, Peru. These data will represent the basis for a future analysis devoted to large scale seismic vulnerability assessment, to develop, in a structured and efficient manner, policies and measures for the seismic risk mitigation. Starting from the collection of available data and from the historical analysis of the urban development of the center, also accounting for earthquakes of the past, the most representative architectural typologies are identified. Moreover, statistical analyses are carried out, in order to detect the most recurrent structural details. On these bases, the main potential fragilities are identified, giving a preliminary idea of the structural behavior of the considered buildings under seismic forces.

Keywords: Structural survey · Seismic vulnerability · Historic center
Inca architecture · Colonial arquitecture

1 Introduction

Seismic risk of cultural heritage is a matter of particular concern: mitigation actions are necessary and urgent, in order to avoid irremediable losses of valuable assets that, apart from cultural issues, often represent the main factor influencing the economy of large worldwide territorial areas. A meaningful example is the historical center of Cusco, in Peru, which is one of the main touristic attraction in the world, hosting about 1.2 million of tourists per year. In fact, although the several buildings transformations carried out in the last years, mainly from dwellings to shops or hotels, in order to favor the economic development of the city, this historic center remains a valuable case of superimposition of three historic phases: the Inca period, the Colonial period and the Republican period. The succession of these historical phases not only determined the formation of a unique and well identifiable architectural style, but also influenced the quality of the buildings.

Cusco is located in a territory with medium to high seismicity and the numerous earthquakes that struck the city in the past stressed on the vulnerability of adobe structures. For this reasons, specific measures of mitigation have to be undertaken in the next future. Based on this premise, this paper describes the first steps of a wide research activity devoted to the assessment of the seismic vulnerability of the historic center of Cusco, Peru, within large scale concepts. This propaedeutic activity consisted in the identification of the main building typologies and structural details, which will be considered for the development of vulnerability assessment methods in the future.

2 Seismic Vulnerability Assessment at Urban Scale

The data survey shown in this paper represents the first step of a wide research activity whose main outcome will be the vulnerability assessment at large scale of the historic center of Cusco.

Seismic vulnerability assessment at urban level can be carried out according to different methodologies that have to be selected owing to the desired results, the availability of data on the stock of buildings that form the historic center, the effort that the evaluator can put in the field depending on the available resources [1].

Usually, it is possible to develop three types of methods: (i) Damage Probability Matrices (*DPMs*), (ii) Vulnerability Indices (*VIs*), and (iii) Capacity Curves (*CCs*) based methods [2].

The first methodology considers the damage scenarios that resulted after earthquakes of the past that hit historic centers similar to the analyzed one, as well as the percentages of buildings that undertook, during these earthquakes, pre-established damage levels/limit states. The collected frequencies represents, for the studied historic center, the probability of attaining the related damage levels under earthquakes of similar magnitude. An example of these matrices is reported in [3], which refers to the three naves churches of Abruzzi.

VIs methodologies deal with the most important sources of fragility that influence the buildings behavior during a seismic event. These sources are evaluated by means of engineeristic judgements in order to define, for each building, a vulnerability index. All the vulnerability indices are therefore used for outlining a vulnerability function that, in turn, is used, under specific hypothesis for predicting damage scenarios [2].

Finally, the *CCs* methods are carried out on the basis of information that concern the geometrical and mechanical characteristic of the observed buildings during in-site observations. These features are included in analytical models that serve to carry out non linear analyses. The response of the buildings, determined by the detecting the performance points on the building capacity curves, allow to predict the damage levels of the structures when these are shaken by earthquakes of different magnitudes. The information required by this approach is based on limited number of buildings.

Within the research framework described above, the data reconnaissance described in this paper is finalized to the setup of a *VI* empirical method. To this aim, a suitable form for the data collection is proposed. This will be described in Sect. 4.

3   Historical Evolution of the Historic Center

The urban development of Cusco is the result of a complex historical process; it is possible to identify some phases [4]: (*a*) the capital of the Inca empire, (*b*) the colonial city, built on pre-existing walls and (*c*) the Republican era, after the War of Independence, when in the first half of the nineteenth century Cusco undertook a strong economic decline, which also affected the quality of the urban fabric. Although this economic crisis lasted until the beginning of the next century, Cusco continued to be the most valuable example of city with a strong identity [5], despite the two earthquakes that destroyed it almost completely, in 1650 and in 1950 [6]. As a matter of fact, the undisputed historical-cultural value of Cusco remains unchanged, even if threatened by the intense process of urbanization and structural transformation that still characterizes its historic center [7].

The last century represented the final phase of the development of the city. In fact, in the first decades of the twentieth century, the urban system began to be improved, after a long period of neglect. In 1920 the Municipality approved a project to transform the road network, including a first minimal expansion towards the south-east area. Furthermore, tourism began to be considered a chance for the development for Cusco. In the following decade, the preparations for the commemoration of the IV Centenary of the Spanish Foundation of Cusco began. Starting in 1940, important works were carried out to improve the road system, and the canalization and coverage of the rivers that cross the city center was completed.

Before the earthquake of 1950, Cusco was characterized by the largest population density ever. The expansion of new urban areas increased considerably. At the same time, the old buildings, lacking of sanitary facilities and unsuitable for housing such quantities of inhabitants, have been expanded occupying the free space in the courtyards. Generally the enlargements showed poor construction quality.

After the earthquake of 1950, the oldest part of the city began to be transformed paying only little attention only to the historical-architectural quality. In fact, while the protection of architectural values was focused on monumental buildings (churches and palaces), residential buildings were often demolished and replaced with poor constructions. Moreover, large areas of the historic center were deeply modified in order to accommodate the new needs of tourism, replacing the original residential function. Furthermore, in order to encourage the use of cars, roads widening operations were undertaken, for this reason many façades were demolished and reconstructed in a backward position.

On the contrary, in areas not affected by tourism development, the lack of maintenance caused a general deterioration of the buildings. As a consequence, several crumbling buildings collapsed during the 1986 earthquake. Many of them were re-built identically, especially in the public parts facing the streets, while in the inner courtyards some of the damaged enlargements were demolished.

4 Historic Center Survey

As stated before, the definition of the actual state of the buildings is the basis for the seismic vulnerability assessment at urban scale.

Thereby, an ongoing extensive survey has been carried out, collecting data for a total of 41 blocks of the 139 blocks included in the "Area of the World Heritage Property", for a total of 549 buildings. Also, parallel to the survey, a data geo-referencing system (GIS type) is being developed. This system will allow the generation of thematic maps that will enable to evaluate effectively the collected data.

Data collection has been carried out through a dedicated survey form divided in 4 Sections: (a) Survey Basic Information; (b) Building Identification and General Characteristics; (c) Building Structural Characteristics; (d) Escape-Rescue Routes.

The section (a) of the survey form collects some general information useful for the classification and organization of data, such as the identification of the person/group carrying out the survey and the date and time of the survey.

The main purpose of section (b) of the survey form is to identify and define the typology of the building. In Table 1 the data collected in the section (b) are listed and briefly described.

As for the building identification, the blocks belonging to the historic center have been numbered, next, the buildings of each block have been numbered. The identification code formed by the block and building numbers (ID.Block_ID.Building) allows a precise geo-referencing.

As for the building typology, six categories have been defined. The first, called "Simple Building", includes all buildings with one or two storey, an inter-storey height between 2 and 3.5 [m] and a maximum bay-span of approximately 5 [m]. The second category, called "Tall Simple Building", differs from the first only by the number of storey (≥ 3). The third category, called "Important Building", concerns buildings with at least two storey, with an average inter-storey height between 3.5 and 5.0 [m] and a bay-span above 5 [m]. Generally, buildings belonging to the third category, although presenting larger dimensions, are structurally similar to those of the first and second category. The fourth category, called "Monumental Building", includes the churches. The fifth category, called "Special Building", includes special facilities such as sports facilities, parking-structures and markets. Examples of the different typologies are shown in Fig. 1. In the sixth category, called "Other", includes all the structures that do not belong to the previous categories.

As can be seen from Fig. 2(a), the "Simple Building" typology is the most widespread. Considering an average inter-storey height equal to 3 [m], it can be deduced that the average height of the two-storey buildings, which represent the 74.6 [%] of the total surveyed, is 6 [m].

Most of the surveyed buildings presents a mixed use destination, commercial/services on the first floor and residential/hotel on the upper floors. Figure 2 (b) shows the results in terms of the intended use.

Table 1. Survey form section (b), Data entry index, description and main results

Data Entry	Description and main results		
Building identification			
Block ID	Block ID number		
Building ID	Building ID number		
Typology	Building typology (Refer to Fig. 1(a))		
Name	Building name (if available)		
Address	Building address (Number, Street)		
Building general information			
Inspection	Defines if the building inspection is possible	Yes	14.9 [%]
		No	47.2 [%]
		Partially	37.9 [%]
Position	Define the building position in the block, to evaluate the influence of the buildings aggregate	Corner	23.3 [%]
		Side	70.5 [%]
		Inside	4.7 [%]
		Other	1.5 [%]
Topography	Define the site topography, to evaluate the local seismic response	Plain	66.7 [%]
		Hillside	32.0 [%]
		Crest	1.3 [%]
External hazards	Defines the presence of external hazards that affect the stability and safety of the structure. The 10.0 [%] of buildings are at risk due to the danger of collapsing adjacent structures		
Storey	Number of storey above the ground: 14.4 [%] 1 Storey – 74.6 [%] 2 Storey – 8.9 [%] 3 Storey		
	Number of storey below the ground: 80.1 [%] 0 Storey – 10.0 [%] 1 Storey		
Storey height	Average storey height: 71.6 [%] $\leq$ 4.0 [m] – 28.4 [%] > 4.0 [m]		
Free sides	Building free sides, to evaluate the interaction with adjacent structures: 26.8 [%] 1 Side – 59.2 [%] 2 Side		
Exterior condition	Scale to define building exterior condition (plaster, roof tiles, …):	Good	48.6 [%]
	"Good" - Good condition;	Average	42.1 [%]

<div align="right">(continued)</div>

Table 1. (*continued*)

| Data Entry	Description and main results		
	"Average" - Sufficient conditions, with signs of deterioration;	Bad	8.2 [%]
	"Bad" - Insufficient condition, need for restoration interventions;	Ruins	1.1 [%]
	"Ruins" - Compromised condition, need for reconstruction;		
Valuable elements	Define the presence of elements with artistic/architectural/historic value. The 16.4 [%] of the buildings have decorative elements, the 1.1 [%] have statues and the 0.5 [%] have wall paintings		
Structural condition	Scale to define building structural condition:	Good	53.9 [%]
	"Good" - Stable structures to gravity and seismic loads;	Sufficient	37.2 [%]
	"Sufficient" - Stable structures to gravity loads;	Insufficient	8.2 [%]
	"Insufficient" - Instable structures;	Bad	0.7 [%]
	"Bad" - Completely or partially collapsed structures;		
Primary Occupancy	Defines the intended use of the building. (Refer to Fig. 1(b))		
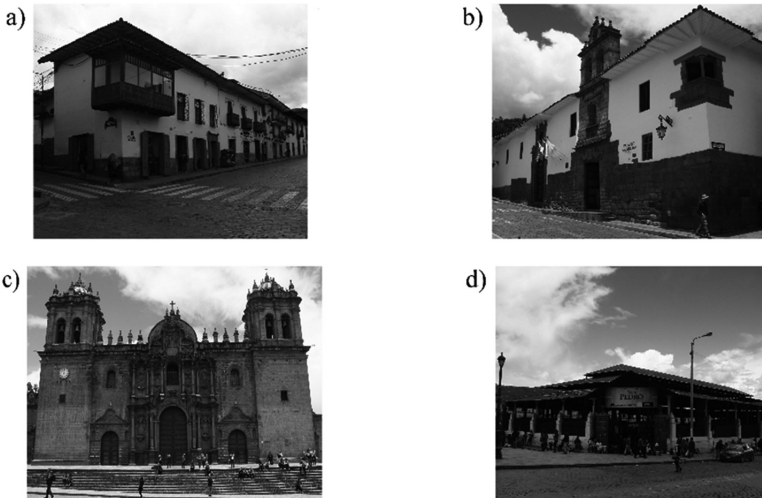
Fig. 1. Building Typology: (a) "Simple" – (b) "Important" (Nazarena Palace) – (c) "Monumental" (Cusco Cathedral) – (d) "Special" (San Pedro Market)
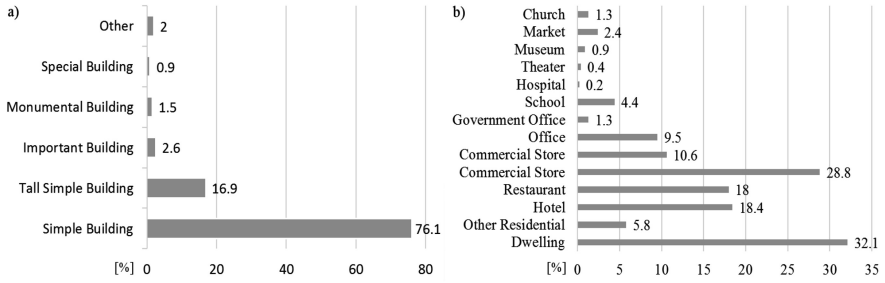
Fig. 2. (a) Buildings typology – (b) Use Destination

In section (c) of the survey form information about the structural characteristics of the building are collected. The analysis of the structure takes place by parts: (a) "Main structure" (seismic-resistant system); (b) "Floor slab" and "Roof" (seismic mass, degree of connection with the vertical elements, rigid diaphragm); (c) "Façade" (stability against the overturning mechanisms); (d) "Base" (stone base typical of traditional architecture). In Table 2 the data collected in the section (c) are listed and briefly described.

The buildings of the historic center have undergone several transformations and renovations making difficult the identification of structural types. Figure 3(a) shows that the types of the "Main structure" and the "Roof structure" are clearly recognized in the 70.0 [%] of the cases, while for a 23.0 [%] of the cases they have been just deducted. As for the "Floor structure", the percentage of clearly identification falls to 50.0 [%] and for a 25.0 [%] of the cases the identification is not possible. Figure 3(b) shows the results regarding the "Main structure" types. The adobe structures represent the 76.1 [%] of the analyzed sample, while the reinforced concrete structures represent the 18.6 [%].

In section (c) of the survey form the data concerning the streets, that represent the main escape and rescue routes, are collected. In Table 3 the data collected in the section (d) are listed and briefly described.

The results collected in Table 3 can be related to other data, such as the width of the streets and the type and characteristics of the façades (therefore the behavior of the façades). The data show that 14.4% of the inspected streets are less than 2.0 [m] wide. This means that in case of a seismic event, the debris produced by the collapse of the façades may obstruct the roadway, preventing the evacuation of buildings and the circulation of emergency vehicles. This simple example demonstrates how it is possible to use the collected data to determine the possible interactions between the various components of the system.

Table 2. Survey form section (c), Data entry index, description and main results

Data entry	Description and main results		
General information			
Determination of structural typology	Defines the knowledge level of the "Main Structure" of the "Floor Structure" and "Roof Structure". (Refer to Fig. 2(a))		
	"Clearly Recognized" - Structural typology evident, precisely determined;		
	"Assumption" - Structural typology not evident, determined by assumptions;		
	"Unknown" - Unable to determine the structural typology;		
Structural elements	Define the presence of structural elements which can significantly affect the structural response. The 14.4 [%] of the buildings have stone portals, the 17.1 [%] have colonnades, the 10.0 [%] have arches while the 31.5 [%] have balconies		
Construction details	Define the presence of construction details which can significantly affect the structural response. The 12.2 [%] of the buildings have ties and rods, the 13.1 [%] have horizontal collars and the 6.2 [%] have reinforced corners		
Main Structure			
Type	Define the type of main structure. (Refer to Fig. 2(b))		
Anomalies	Define the presence of structural anomalies of the main structure which can significantly affect the structural response. The 12.4 [%] of the buildings have irregular structure (plan/elevation), the 3.6 [%] have poor connection between vertical and horizontal structures		
Façade (to evaluate the out-of-plane mechanisms)			
Type	Define the type of façade structure	Adobe	78.5 [%]
		Masonry	4.2 [%]
		Reinforced concrete	14.0 [%]
		Other	3.3 [%]
Anomalies	Define the presence of structural anomalies of the façade structure which can significantly affect the structural response. The 13.7 [%] of the buildings have façade with no structural function. The 2.7 [%] of façade present poor connections with the main structure, the 5.3 [%] present not aligned openings, the 4.7 [%] present big openings (>50 [%] of façade width) and the 10.7 [%] are out of plumb		
Thickness	Façade thickness [cm]	≤ 30 [mm]	52.5 [%]
		30 [m] $< - \leq 50$ [cm]	26.2 [%]
		50 [m] $< - \leq 100$ [cm]	14.4 [%]

(*continued*)

Table 2. (*continued*)

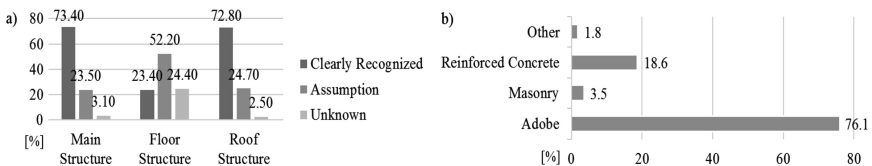| Data entry	Description and main results		
		> 100 [cm]	6.9 [%]
Building Base			
Type	Define the presence and the type of base structure	Inca stone	22.4 [%]
		Spanish stone	14.6 [%]
		Stone	33.2 [%]
		Masonry	0.7 [%]
		No base	29.1 [%]
Height	Base height [m]. The 46.8 [%] of the buildings have a base height of 1.0 [m], the 14.4 [%] have a base height of 2.0 [m] while the 9.7 [%] have a base height $\geq$ 3 [m]		
Horizontal Structure			
Floor type	Define the type of floor structure	Wood	59.3 [%]
		Reinforced concrete	33.1 [%]
		Steel	2.9 [%]
		Other	4.7 [%]
roof type	Define the type of roof structure	Wood	65.0 [%]
		Reinforced Concrete	10.6 [%]
		Steel	1.6 [%]
		Other	22.8 [%]

Fig. 3. (a) Structural typology identification – (b) Main structure typology

Table 3. Survey Form Section (d), Data Entry Index, Description and Main Results

Data entry	Description and main results		
Doors			
Characteristics	Define doors characteristics (number, size, etc.). The 55.9 [%] of the buildings have more than 1 door. The 61.2 [%] of the doors have a width $\geq$ 1.5 [m]. The 22.8 [%] of the doors present steps or obstacles (no easy exit)		
Sidewalk			
Width [m]	Define the presence and the width of the sidewalk	No Sidewalk	13.8 [%]
		≤ 1 [m]	52.5 [%]
		>1 [m]	33.7 [%]
Street			
Width [m]	Define the width of the street	≤ 2 [m]	14.4 [%]
		2 [m] $< - \leq$ 5 [m]	62.3 [%]
		>5 [m]	23.3 [%]
Surface	Define the surface material of the street	Asphalt	21.5 [%]
		Concrete	9.8 [%]
		Stone	68.0 [%]
		Soil/Gravel	0.7 [%]
Various	Define street characteristics. The 28.4 [%] of the streets present obstacles to circulation of vehicles (steps, poles, holes)		

5   Conclusions

In this paper, some of the main characteristics of buildings from the historic center of Cusco have been shown. These have been collected by using a specific form, which has been specifically setup by the authors, and statistically represented in terms of frequencies. The here presented study is a first step of a wider research activity that will allow in the next year to provide a robust large scale vulnerability assessment of historical centers.

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