Seismic Retrofitting Project: Assessment of Prototype Buildings

Volume 1

Research Report

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In collaboration with Dina D'Ayala,
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Los Angeles 2012

The Getty Conservation Institute

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The Getty Conservation Institute works internationally to advance conservation practice in the visual arts—broadly interpreted to include objects, collections, architecture, and sites. The GCI serves the conservation community through scientific research, education and training, model field projects, and the dissemination of the results of both its own work and the work of others in the field. In all its endeavors, the GCI focuses on the creation and delivery of knowledge that will benefit the professionals and organizations responsible for the conservation of the world's cultural heritage.

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CHAPTER 1

Background

1.1 Introduction

For millennia humans have constructed buildings of earth. In places ranging from ancient archaeological sites to living cities, from the vernacular to the monumental, earth is used as both a structural and a decorative material (Figs. 1.1, 1.2). The remarkable diversity of earthen heritage presents equally complex conservation challenges. As an example, while only ten percent of the cultural sites on UNESCO's World Heritage List are earthen, fifty-seven percent of these are included on the List of World Heritage in Danger.

Earthen buildings, typically classified as unreinforced masonry structures, are vulnerable to earthquakes and subject to sudden collapse during a seismic event—especially if a building lacks proper and regular maintenance. Historic earthen sites located in seismic areas are at high risk of being heavily damaged and even destroyed.

1.2 Institutional Background and Project Partners

For nearly two decades, the Getty Conservation Institute (GCI) has been a recognized leader in developing methodologies and setting standards for the conservation of earthen architectural heritage in California and abroad. The GCI has

FIGURE 1.1
Great Mosque, Djenné, Mali. Regular maintenance of this earthen architectural masterpiece is carried out by the community at an annual festival.
Image: Françoise Descamps.

FIGURE 1.2
Mission San Luis Rey de Francia, Oceanside, California, USA. The church at San Luis Rey, ninth of the California missions, is constructed of unreinforced adobe masonry.
Image: Gail Ostergren.

generated cutting edge research, training programs, publications, and field projects that have deepened the understanding of earthen architecture and its particular vulnerabilities. All of these activities have disseminated research results and built capacity in the field through the organization of workshops and training courses for practitioners, highly-specialized experts meetings and colloquia, and major international conferences.

During the 1990s, the GCI carried out a major research and laboratory testing program—the Getty Seismic Adobe Project (GSAP)—which the GCI and the field are now building upon. The GSAP investigated the performance of historic adobe structures during earthquakes and developed cost-effective retrofit methods that substantially preserve the authenticity of these buildings. Results of this research have been disseminated in a series of publications, both in English and Spanish.

In April 2006, the GCI hosted the GSAP Colloquium at the Getty Center in Los Angeles. This meeting assembled an interdisciplinary group of sixty international specialists to assess the impact and efficacy of the GSAP seismic retrofitting recommendations and to discuss where and how GSAP guidelines have been implemented; the colloquium proceedings were published in 2009. The participants concluded that the GSAP methodology was reliable and effective, but its reliance upon high-tech materials and professional expertise was a deterrent to it being more widely implemented.

To address this, the GCI has joined forces with the Ministerio de Cultura del Perú (formerly the Instituto Nacional de Cultura), the Department of Architecture and Civil Engineering at the University of Bath in the United Kingdom, and the Escuela de Ciencias e Ingeniería (School of Engineering) at Pontificia Universidad Católica del Perú to form the Seismic Retrofitting Project (SRP). Building on the earlier work of the GSAP, the SRP will marry traditional construction techniques and materials with methodologies that have been created for use in the developing world.

1.3 Seismic Retrofitting Project

The ultimate objective of the Seismic Retrofitting Project is to adapt the GSAP guidelines in countries where equipment, materials, and technical skills are not readily available by providing low-tech seismic retrofitting techniques and easy-to-implement maintenance programs for historic earthen buildings in order to improve their seismic performance while preserving their historic fabric. Using Peruvian building prototypes as case studies, the project aims to design and test these techniques; provide guidance for those responsible for implementation, including architects, engineers, and conservators; and, work with authorities to gain acceptance of these methods, with the goal of ultimately including them as part of the *Norma Técnica de Edificación NTE E.080 Adobe (Technical Building Standard E.080 for Construction in Adobe)*[1] within the Peruvian National Building Code. Peru has been selected as the location for the work due to the current and historical knowledge and professional interest in the subject; the ongoing revision of the *NTE E.080*; the existence of potential partners for implementation of these techniques on a model conservation project; and, background work already completed by the GCI, such as the *Damage Assessment of Historic Earthen Buildings After the August 15, 2007 Pisco, Peru Earthquake* (Figs. 1.3, 1.4).

FIGURE 1.3
The earthen Church of El Carmen, Chincha, Peru. The bell tower collapsed during the 2007 Pisco earthquake.
Image: Philippe Garnier, for the GCI.

FIGURE 1.4
The earthen Capilla Virgen Concebida de Kuchuwasi, near Cusco, Peru.
Image: Claudia Cancino.

1.3.1 Project objectives

- Design low-tech seismic retrofitting techniques, using locally available materials and expertise for Peruvian historic building types that have potential for wider application in other countries;
- Validate retrofitting techniques with current scientific knowledge;
- Obtain the recognition, approval, and promotion of the techniques by local authorities in Peru;
- Develop a methodology to assess earthen historic sites, which can be used as a tool for making decisions about maintenance and interventions and has potential for wider application in other countries;
- Develop guidelines for site assessments and implementation techniques, highlighting the significance that ongoing evaluation, maintenance, and repair play in improving the seismic performance of historic earthen buildings; and
- Develop a model conservation project that demonstrates the implementation of the techniques.

1.3.2 Project phases

All project activities have been divided in four phases: (I) feasibility and research; (II) methodology; (III) testing and modeling; and, (IV) dissemination and implementation. The planned activities for each phase are described in greater detail below.

1.3.2.1 Phase I - Feasibility and research

- **Feasibility**: Test the project feasibility, goals, and outcomes by consulting with different professionals with expertise in the field of conservation and seismic retrofitting, and establish an external peer review group.
- **Modes of failure**: Gather information on modes of failures of the already-identified prototypes. This research study will analyze existing historic data regarding the way earthen buildings behave during a seismic event using the findings from the damage assessments performed after the 2007 Pisco,

Peru earthquake as well as the 1996 Northridge, California (USA) earthquake.

- **Selection and assessment of building prototypes**: Identify four building typologies that are priorities for the application of seismic retrofit techniques based upon level of significance, where solutions are most needed, and which modes of failure and their corresponding reinforcing techniques will have the most widespread application in Peru and other countries in Latin America; and perform construction assessments of the selected building prototypes.
- **Low-tech / alternative / vernacular / historic solutions for retrofitting**: Collect historic information on traditional and seismically-resistant construction materials and techniques developed over time in Peru.
- **Previous interventions already implemented in Peru**: Collect information from other professionals working in the field of conservation in Peru regarding the seismic performance of already existing/implemented repairs on earthen historic buildings in recent decades.

1.3.2.2 Phase II - Methodology

- **Proposal for numerical modeling of earthen sites**: In collaboration with the Department of Architecture and Civil Engineering at the University of Bath (BATH), develop a proposal for the numerical modeling and seismic analysis of the identified building prototypes.
- **Proposals for experimental testing of building types**: In collaboration with the School of Engineering at Pontificia Universidad Católica del Perú (PUCP), develop a proposal for static and dynamic testing of the identified building prototypes for the study of their structural performance during an earthquake, as a complementary technique to the numerical modeling and analysis.
- **Peer review meeting**: Organize a peer review group meeting to discuss the project design and methodology, the construction assessment of the selected prototype buildings, and proposals for the numerical modeling and experimental testing of the prototypes.
- **Capacity building activities**: In collaboration with national institutions, potentially develop workshops regarding the methodology used during phases I and II of the project for the construction assessment of earthen sites.

1.3.2.3 Phase III - Testing and modeling

- **Design of retrofitting solutions**: In collaboration with BATH and PUCP, propose suitable retrofitting techniques for the prototype buildings.
- **Testing and modeling of retrofitting technique**s: Verify the effectiveness of the proposed retrofitting solutions by means of numerical approaches at BATH and experimental tests at PUCP.
- **Peer review**: Seek input of peer review group on the design of the retrofitting techniques.
- **Capacity building activities**: In collaboration with national institutions, potentially develop a preliminary series of workshops to build up a national/regional assessment methodology to develop an action plan for the maintenance and repair of historic earthen sites.

1.2.3.4 Phase IV - Dissemination and implementation

- **Dissemination**:
  - Draft peer-reviewed guidelines for the implementation of retrofitting designs and techniques to be considered as a part of the *NTE E.080* and that can be more widely applied in other Latin American countries.
  - Develop guidelines for site managers that practically explain the implementation of retrofitting techniques and include principles for site maintenance that together form the basis of preventive approaches to the conservation of earthen historic buildings in seismic areas.
- **Implementation**:
  - In collaboration with national and international consultants, develop a project proposal for the retrofitting of one or two of the selected building types.
  - In collaboration with a national partner, implement retrofitting project for the site(s).
  - Document the retrofitting project(s) for further dissemination.

1.4 Introduction to Assessment Report

This assessment report has been prepared to synthesize the data obtained for the selected prototype buildings during phase I of the project and is being published during phase II.[2] It is intended to be a useful reference document for the project team as they develop the numerical modeling and seismic analyses of the buildings and the complementary experimental tests, as well as for the peer review group, site managers, and owners. The document will also be used for the dissemination of the assessment methodology to the wider conservation and engineering community.

The report provides a detailed description of the project methodology for the selection and survey (through both non-destructive techniques and limited openings) of the prototype buildings (chapter 2); a description and condition assessment of the selected prototype buildings (chapters 3–6); and, general conclusions on the survey methodology, collected structural data, and structural design and observed behavior of the prototype buildings (chapter 7). A sample of the survey form developed for the project is provided in Appendix A. Appendices B and C include the architectural and detailed propsection drawings prepared for the prototype buildings (the appendices are included in volume 2 of this report). All photographs of the prototype buildings included in the report were taken during the field survey campaigns carried out in 2010, unless otherwise noted.

It is important to note that this assessment report reflects the project team's understanding of the buildings prior to the results of the numerical modeling and seismic analyses and experimental testing. Thus, some of the preliminary findings included in this report are subject to revision upon the completion of phase III.

Notes

1 This technical norm—commonly known as *Norma del Adobe*—was created to regulate seismically-resistant new adobe construction and was added for the first time to the Peruvian National Building Code in 1987. The *NTE E.080* was originally designed by a group of architects and engineers who were members of the *Norma del Adobe* committee (NORMA), created at the Servicio Nacional de Capacitación para la Industria de la Construcción (SENCICO – National Training Service for the Construction Industry). SENCICO is a governmental agency that is part of the Ministry of Housing and Construction. Among its functions, it develops norms, standards, and regulations for building design, construction materials, and technologies in order to improve construction quality, costs, and life safety assurance. The *NTE E.080* was reviewed for the first time in 1999 and the revised edition was published in 2000. It is currently being expanded to include a section on interventions in historic earthen buildings.

2 The data collected during phase I of the project was obtained during two field survey campaigns carried out in 2010. Thus, this report reflects the condition of the four prototype buildings in 2010 and does not incorporate any subsequent changes in condition resulting from seismic activities or other environmental factors.

CHAPTER 2

Methodology

2.1 Previous Assessments

The Seismic Retrofitting Project methodology was informed by the work of earlier post-earthquake assessments, such the GCI's *Damage Assessment of Historic Earthen Buildings After the August, 15, 2007 Pisco, Peru Earthquake*. Such assessments offer an opportunity to understand why buildings fail and provide information that can serve as the basis for the improvement of their seismic performance. For centuries, lessons learned from earthquakes and other natural disasters have been used to advance construction techniques. More recently, such lessons have fostered the development of the engineering and historic preservation disciplines, as well as the testing and review of current building codes and disaster management policies and procedures.

The history of Peruvian architecture exemplifies this process. In response to their understanding of the effects of seismic activity on earthen structures, early Peruvian cultures developed reinforcement techniques to enhance their earthen construction systems. The tradition continues today with the inclusion of the *Norma Técnica de Edificación NTE E.080 Adobe (Technical Building Standard E.080 for Construction in Adobe)* in the Peruvian Building Code. This technical standard provides a series of recommendations to reduce the seismic vulnerability of new adobe construction.

On August 15, 2007, an earthquake with a moment magnitude (M_W) of 8.0 and a maximum local Modified Mercalli Intensity (MMI) of VII–VIII hit the southern coast of Peru. Preliminary reports indicated that a large number of historic earthen sites located in the communities of Cañete, Chincha, Pisco, Ica, and Huancavelica were severely damaged (Figs. 2.1, 2.2).

FIGURE 2.1 (LEFT)
Church of Guadalupe, damaged by the 2007 Pisco earthquake, 2007. Image: Claudia Cancino.

FIGURE 2.2 (RIGHT)
Church of Humay, damaged by the 2007 Pisco earthquake, 2007. Image: Claudia Cancino.

After the 2007 earthquake, a multidisciplinary team of national and international earthquake engineers, preservation architects, and conservators—convened by the GCI—visited a total of 14 historic earthen sites, rapidly documented them, and evaluated the damage to these sites. The team concentrated on recording existing conditions such as abandonment, deterioration, or structural alterations over time, with the ultimate objective of understanding the impact of such conditions on the buildings' seismic performance. The assessment, which was organized in response to a request from the former Instituto Nacional de Cultura del Perú (now the Ministerio de Cultura del Perú), is available on the GCI's website.

The lessons learned from the Pisco earthquake assessment informed the process of identifying prototype buildings to be studied as part of the Seismic Retrofitting Project, as well as the development of the methodology to survey the condition of those prototype buildings.

2.2 Selection of Prototype Buildings

As part of the first phase of the Seismic Retrofitting Project, it was a determined that up to four building typologies would be selected for study in future project phases. Each selected typology was to represent buildings that are priorities for seismic retrofitting based upon their level of historic, social, or architectural significance; the current lack of—and thus greater need for—retrofitting solutions for the particular prototype; and their demonstration of typical modes of failure, so that the reinforcing techniques developed as part of the project would be able to be more widely applied to other earthen sites in Peru, South America, and other seismic regions of the world.

At the beginning of 2010, the SRP team identified four building typologies that met these criteria. The typologies were:

- **Typology 1**: Residential structure constructed with mud brick and *quincha* (wattle and daub) walls and flat roofs; representative of colonial houses in the historic centers of coastal towns and cities.[1]
- **Typology 2**: Religious structure constructed with thick mud brick walls and quincha vaults and domes; representative of the churches built in coastal cities and preferably located in the region affected by the 2007 Pisco earthquake.
- **Typology 3**: Religious structure constructed with thick mud brick walls, normally decorated with mural paintings, and a wood truss roof; representative of the churches built in the Andes.
- **Typology 4**: Residential structure constructed with two-story mud brick walls and a wood truss roof; representative of the colonial houses built in the historic centers of Andean cities.

A total of 20 sites in Peru were pre-selected for an initial assessment by GCI and Peruvian architects, architectural historians, and engineers; and, those sites were visited in February 2010. The sites were assessed using different criteria that considered if (1) the original structural system was extant, with limited or no interventions; (2) the building was historically significant; (3) the building was representative of one of the four identified typologies; (4) the owner/manager would facilitate access to the site for study, with no further expectations for the implementation of a retrofitting or repair project; (5) the site and surrounding area would be safe for the team to survey and carry out other necessary work of the project; (6) the structure exhibited deterioration mechanisms/conditions that could impact its seismic performance; (7) the site was easily accessible by foot and/or by car with proper lodging close in the vicinity; (8) there was existing and readily available historical and architectural data for the site; and, (9) the site had visibility, or aesthetic value. Each site was given a score of 1–10, with 10 being the highest, for each of the criterion described above; and, each of the criterion was equally weighted to determine the final score. Table 2.1 provides a list of the 20 visited sites, as well as a summary of their assessment scores.

Table 2.1 Initial assessment scores for 20 preselected sites

Name of site	Original structure (no interventions)	Historical value	Significance (representative of a typology)	Availability (approachable owner)	Security (safe for project staff)	Representative pathologies	Accessibility (location)	Extant historical and architectural data	Visibility	**TOTAL**
Hospicio Ruiz Dávila, Lima	6	7	8	1	4	6	6	4	4	**46**
Quinta Heren, Lima	8	8	8	8	4	7	5	5	5	**58**
Hacienda San Juan Grande, Lima	5	7	6	2	2	6	6	4	5	**43**
Hotel El Comercio, Lima	6	8	8	10	8	8	8	9	6	**71**
Cathedral of Ica, Ica	9	7	7	6	9	10	8	6	8	**70**
Church of San Antonio, Mala	5	5	8	9	7	9	4	4	3	**54**
Church of San Juan, Ica	8	5	8	9	7	9	4	4	3	**57**
Church San Luis, Cañete	4	5	8	10	7	9	4	4	3	**54**
Church Santuario de Yauca, Ica	7	5	8	8	7	9	4	4	3	**55**
Church of Andahuaylillas, Cusco	7	10	8	7	7	3	5	7	10	**64**
Church of Canincunca, Cusco	6	9	8	7	7	3	4	6	8	**58**
Church of Marcapata, Cusco	10	8	8	8	6	8	2	6	8	**64**
Church of Kuchi Wasi, Cusco	10	8	7	8	6	5	2	6	7	**59**
Church of Kuño Tambo, Cusco	10	8	8	10	8	9	3	6	8	**70**
Church of Rondocan, Cusco	7	8	8	9	8	6	2	6	5	**59**
Casona Garrido Mendivil, Cusco	6	8	6	5	8	5	9	7	6	**60**
Casa Arones, Cusco	8	8	9	10	8	9	10	8	6	**76**
Casa Alonso del Toro, Cusco	6	8	6	4	4	5	8	7	6	**54**
Casa Serapio Calderón, Cusco	7	8	6	4	3	6	8	7	6	**55**
Casa Concha, Cusco	5	9	7	8	8	4	8	8	8	**65**

The buildings receiving the highest scores, and thus selected for further study, were:

- **Typology 1** – **Hotel El Comercio**: A nineteenth century three-story mud brick and quincha building in the historic center of Lima (Fig. 2.3).
- **Typology 2 – Cathedral of Ica**: An eighteenth century church with thick mud brick walls and quincha vaults and domes that was damaged by the 2007 Pisco earthquake (Fig. 2.4).
- **Typology 3 – Church of Kuño Tambo**: A seventeenth century building constructed with thick mud brick walls and a wood truss roof and located in a small Andean village near Cusco (Fig. 2.5).
- **Typology 4 – Casa Arones**: A seventeenth century two-story mud brick building with a wood truss roof, located in the historic center of Cusco (Fig. 2.6).

FIGURE 2.3
Typology 1: Hotel El Comercio, historic center of Lima.
Image: Amila Ferron.

FIGURE 2.4
Typology 2: Cathedral of Ica, Ica.
Image: Sara Lardinois.

FIGURE 2.5
Typology 3: Church of Kuño Tambo, Cusco region.
Image: Wilfredo Carazas, for the GCI.

FIGURE 2.6
Typology 4: Casa Arones, historic center of Cusco.
Image: Sara Lardinois.

In addition to the previously-described selection criteria, each site had its own unique characteristics which increased its study value; however, because of the uniqueness of these characteristics, they could not be factored into the final assessment score. Despite this, these characteristics are worth noting and are provided in the summary descriptions of each of the selected prototype buildings below.

Hotel El Comercio, which received the highest scores for typology 1, was selected for further study. Its value as a prototype building can be summarized as follows:

- It is representative of residential courtyard or patio buildings, known as *casonas*, that are typical in colonial era cities along the coast; although, the third story makes it taller than many other two-story casonas.
- It exemplifies typical Peruvian earthen construction techniques with mud brick masonry walls at the first floor, quincha walls at the upper floors, and flat wood-framed floors and roofs.
- Similar to many historic buildings in downtown Lima and other colonial cities in South America, Hotel El Comercio has become more structurally complex due to many changes in use and alterations over its history.
- Despite the fact that it is structurally more complex than a traditional casona due to its third floor and alterations, the methods and conclusions of the numerical modeling and experimental testing approach to be utilized in its seismic assessment can be applied to the study of simpler structures.
- Its location at the corner of an urban block that makes it more vulnerable than a building located at the middle of a block.

The Cathedral of Ica, which received the highest scores for typology 2, was selected for further study. Its value as a prototype building can be summarized as follows:

- It is representative of churches along the coast of Peru constructed with mud brick lateral walls, a fired brick façade, and quincha pillars and roofs. Although it is structurally more complex than some of the other churches, any proposed seismic retrofitting measures may be adapted for the less complex churches.
- The cathedral was damaged during the 2007 Pisco earthquake, and thus presents an opportunity to study existing earthquake damage and provide badly-needed solutions for its retrofit (Fig. 2.7).

FIGURE 2.7
Interior view of the Cathedral of Ica, showing damage to the vault after the 2007 earthquake.
Image: Sara Lardinois.

- The cathedral is a highly significant structure—it was declared a national monument in 1982. It has retained this status, despite the damages incurred during the 2007 earthquake.
- Its location at the corner of an urban block makes it more vulnerable than a building located at the middle of a block.

The Church of Kuño Tambo, which received the highest scores for typology 3, was selected for further study. Its value as a prototype building can be summarized as follows:

- It is representative of rural earthen churches in the mountainous interior of Peru and South America, built during the period of the Spanish Viceroyalty, with thick mud brick walls and a wood-framed gable roof. The church has undergone limited alterations and interventions; and, thus, it retains most of its original seventeenth century structural scheme.
- Like many of these rural churches, the site is remote and only accessible by a narrow and winding road through the mountains. This will have a bearing on the types of retrofit measures that can be developed and implemented, as it may be difficult to bring in outside materials, equipment, or expertise.
- Any proposed retrofitting techniques will need to be designed and implemented in such a way that the decorative interior finishes, such as extant wall paintings, are not impacted in the process. This will be the case for many earthen sites located in the area and other seismic regions in the world.

Casa Arones, which received the highest scores for typology 4, was selected for further study. Its value as a prototype building can be summarized as follows:

- It is representative of a typical house in Cusco, dating to the period of the Spanish Viceroyalty, with an interior patio surrounded by stone and fired brick masonry arcades.
- Similar to Hotel El Comercio, its location at the corner of an urban block makes it more vulnerable than a building located at the middle of a block.
- Unlike Hotel El Comercio, it is constructed with two-story mud brick walls and a wood-framed gable roof.

2.3 Assessment Methodology

The project has been structured in different phases, beginning with research and investigation of the selected prototypes and ending with dissemination and implementation of the tested retrofitting techniques. As part of the research and investigative phase, data was acquired through historic research and architectural and structural surveys and investigations. The collected data is summarized in chapters 3–6 of this report, and it will inform the development of the experimental tests and numerical modeling and seismic analyses of the building prototypes in the next project phases.

2.3.1 Survey and investigations

As part of the architectural and structural investigations, the prototype buildings' structural configurations and conditions were documented and assessed through two field survey campaigns carried out in 2010. In order to properly assess the selected sites, various documentation methods were utilized: (1) survey forms targeted to address structural configurations and conditions, largely completed using visual observations; (2) non-destructive investigations, such as thermal imaging; and (3) the opening up of specific areas of the buildings to better understand their internal structural configurations and connections.

2.3.1.1 Survey sectors and forms

As the four prototype sites have different structural configurations, the project team divided each building into sectors for the purposes of the survey. The selection of sectors was based upon how the buildings may perform during a seismic event.

For the residential structures, the selection of sectors was largely based upon the direction of the floor and roof beams and joists. Each residential structure was divided into four sectors per floor. Hotel El Comercio was divided into (a) sector A: the area of the building adjacent to the north corner; (b) sector B: the series of rooms adjacent to the longer northwest lateral façade; (c) sector C: the series of rooms bordering with the adjacent structure to the southwest; and, (d) sector D: the rooms at the southwest side of the patio (Fig. 2.8). Casa Arones was divided into (1) sector 1: rooms along the street to east, Calle Arones; (2) sector 2: rooms along Calle Nueva Alta, including the gallery at the north side of the patio; (3) sector 3: rooms between sector 1 and the main patio; and (4) sector 4: rooms at the south side of the patio, bordering the neighboring structure (Fig. 2.9).

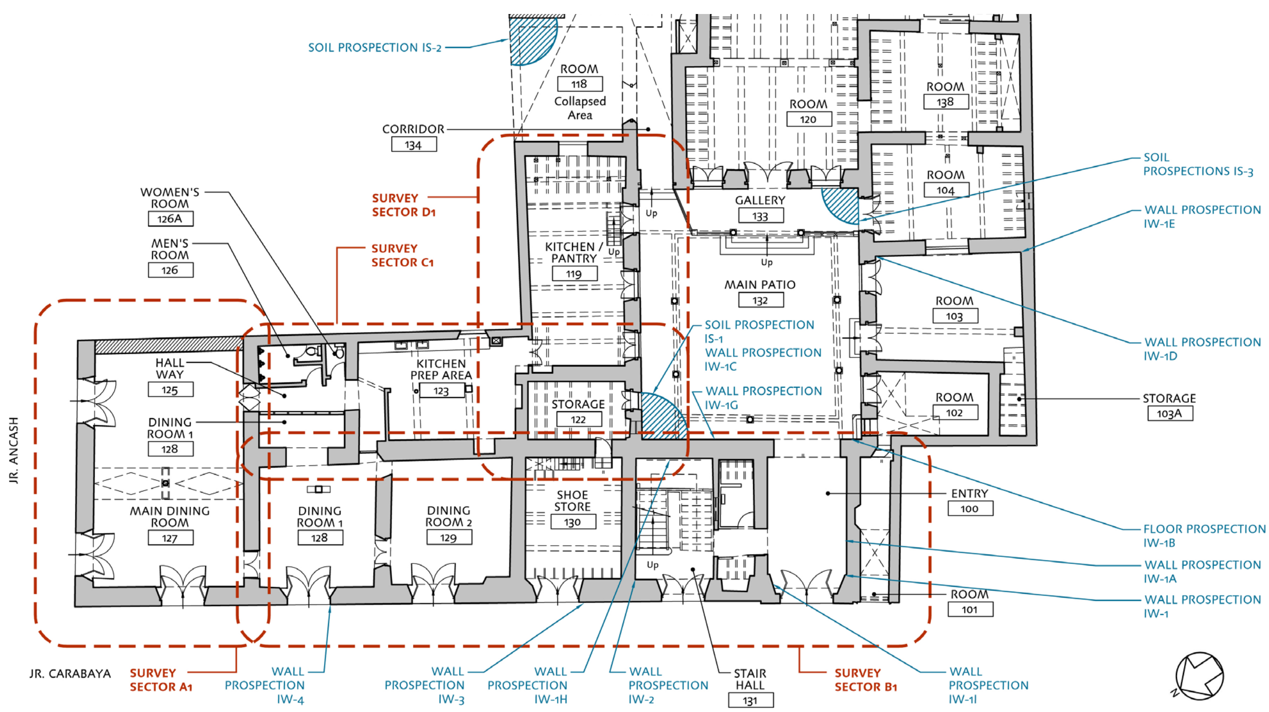


FIGURE 2.8
Hotel El Comercio, survey sectors shown in red. As the first and second patios have a similar configuration, only the first patio and northeast section of the building was were surveyed.
Drawing: Base drawing provided by the Instituto Nacional de Cultura and edited by the GCI.

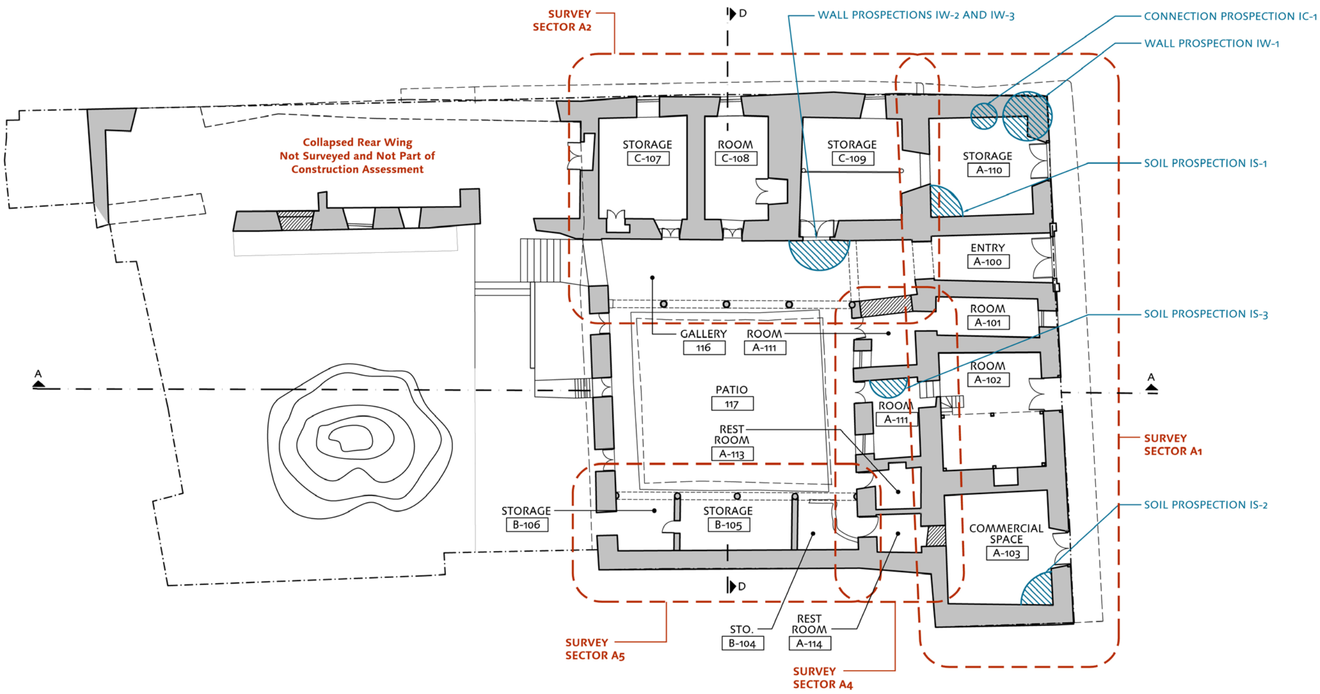


FIGURE 2.9
Casa Arones, survey sectors shown in red.
Drawing: Base drawing prepared by Enrique Estrada and edited by the GCI.

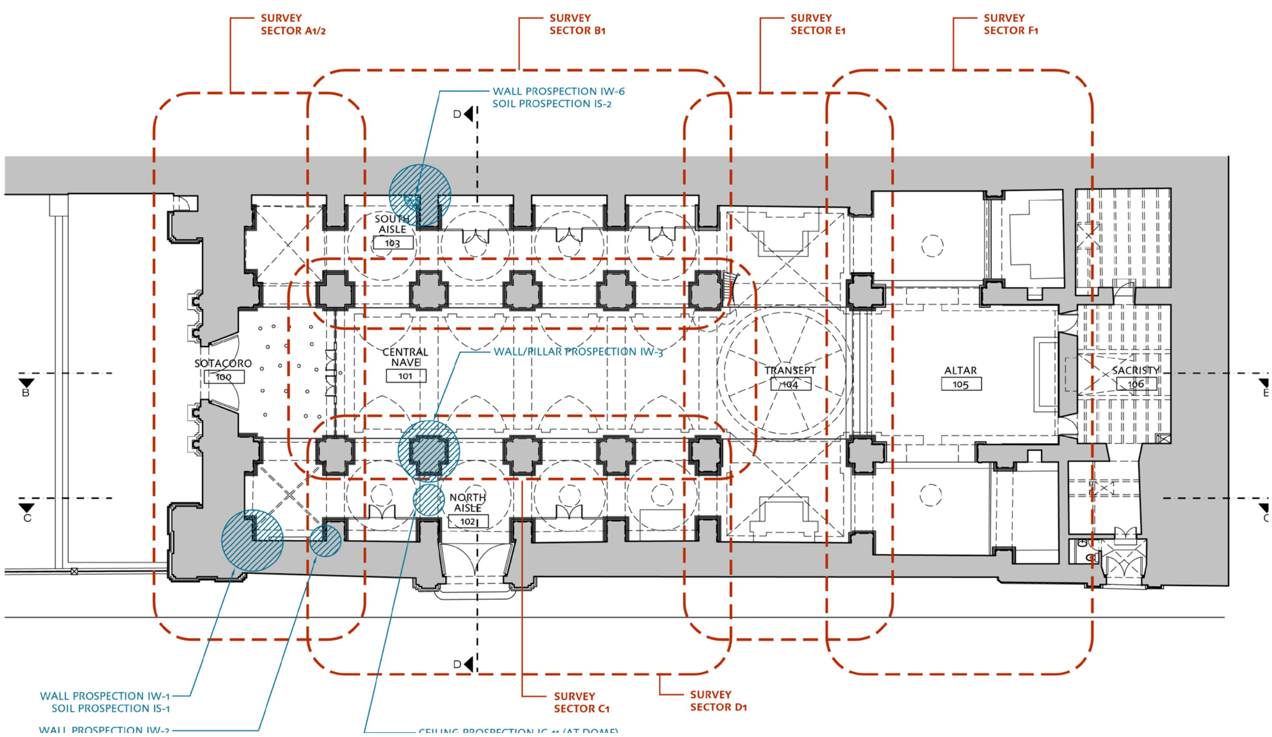


FIGURE 2.10
Cathedral of Ica, survey sectors shown in red.
Drawing: Base drawing prepared by Mirna Soto and edited by the GCI.

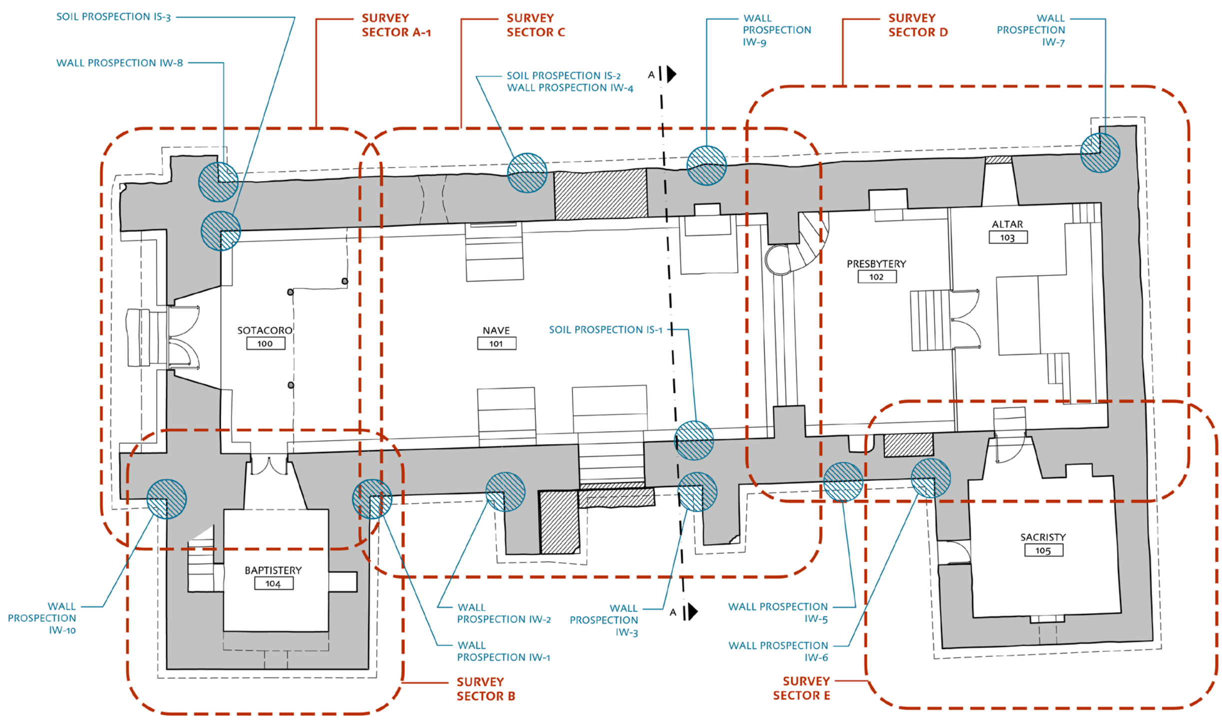


FIGURE 2.11
Church of Kuño Tambo, survey sectors shown in red.
Drawing: Base drawing prepared by Ruben Estrada Tapra and edited by the GCI.

The selection of sectors in the religious structures was based on their architectural configuration. The Cathedral of Ica was divided into six sectors: (a) sector A: the two-story choir loft, *sotacoro* (area under the choir loft), façade, and bell towers; (b) sector B: central nave; (c) sector C: side aisle along the street, Jirón Cajamarca; (d) sector D: side aisle bordering the adjacent structure; (e) sector E: the crossing and transept; and (f) sector F: the altar (Fig. 2.10). The Church of Kuño Tambo was divided into five sectors: (a) sector A: the two-story choir loft and sotacoro; (b) sector B: the baptistery; (c) sector C: the central nave; (d) sector D: the presbytery and altar; and (e) sector E: the sacristy (Fig. 2.11).

A general survey form was developed to gather information on the structure as a whole, and sector-by-sector survey forms were developed to obtain critical information regarding construction techniques, as well as the severity of the structural element conditions (Figs. 2.12, 2.13). The forms were accompanied by detailed drawings graphically indicating the location of construction materials and conditions described in the forms (Figs. 2.14, 2.15).

The general survey form collected the following data for each site:

i. Building information: name and address, original construction date or period, images, and floor plan
1. Building type: casona (one or two stories of adobe / adobe and quincha, two or more stories) or church (adobe walls with quincha vaults or domes / adobe walls with wood truss roof system)
2. Context: within historic district/center, urban, or rural environment; adjacent to other buildings, including the location within the block; close to other buildings, including distances from them; or isolated

3. Setting: flat or sloped
4. Occupancy: unoccupied or occupied (indicating average number of occupants per day and night)
5. Shape in plan: rectangular, square, C, L, or other/mixed
6. Wall density
7. Use: residential, commercial, museum, religious, office, or other
8. Socioeconomic characteristics: economic level of inhabitants and type of ownership (rent / own)
9. General architectural description
10. History of alterations
11. Description of soil configuration/type
12. Level of maintenance: existence of maintenance plan (if yes, by whom and how often) and reports of previous earthquake damage
13. Quality of original workmanship at the roof, ceiling, masonry, and foundations

The following data was collected for each survey sector of a particular building:

1. Sector number, type (courtyard / tower / group of rooms / individual room / roof), and floor level
2. Overall floor plan, indicating the location of the sector in the building
3. Enlarged floor plan of sector
4. Cross sections, elevations, or photos
5. General seismic performance and vulnerability:
    - Shape of the building sector: rectangular, square, C, L, or mixed
    - Average span between walls in x and y directions
    - Wall density
    - Indication if vertical load-bearing walls appear to be attached to the foundation (first floor only) or floor/roof structures (others and last floor)
    - Maintenance: general condition of building sector materials, noting any building elements damaged by previous earthquake(s) that have not been repaired
6. Key plan indicating location of photographs taken to record surveyed conditions
7. Description of sector structural system:
    - Foundations and *sobrecimiento* (base course):
        - Foundations: natural (solid rock / stiff soil / structure rock), man-made (rubble stone masonry / coursed stone masonry), or no foundation (walls sitting on natural unmodified ground), with indication of condition (cohesive / not cohesive)
        - Base course: man-made (rubble stone masonry / coursed stone masonry), with indication of condition (cohesive or not cohesive)
    - Load bearing masonry/quincha walls:
        - Adobe masonry (noting dimensions of block and mortar, if any), rammed earth, fired brick masonry, or stone masonry
        - Quincha walls with wood frames (cane and reed / adobe block infill / fired brick infill)
    - Previous structural reinforcements:
        - Reinforced adobe or fired brick masonry walls with embedded concrete columns

  - Concrete frame with unreinforced adobe or fired brick masonry walls
  - Other reinforcements: iron/steel bars (across walls / inside walls), anchors (top to roof / wall to wall), wooden keys, or isolated concrete or wood beams (located at top of longer walls / shorter walls / across room / around the room)
- Plaster on walls and ceiling (mud / lime / cement / painted surface only), with indication of painted or unpainted finish
- Floors: wood or concrete beams or joists, indicating number of framing elements, dimensions, and spacing
- Roofs: truss, concrete structure, quincha vault/dome, flat, or other, indicating number of framing elements, dimensions, and spacing

8. Conditions impacting seismic performance of sector:

- General conditions: stable or instable
- Condition of the adobe/quincha walls:
  - Total collapse (all walls / half of the walls / one quarter of the walls)
  - Partial wall collapse, not considering the condition of the plaster (at the center / corners / upper section)
  - Settlement of walls (at center / on edges)
  - Corner damage (full height / upper part of the walls)
  - Out-of-plane displacement (inward / outward / bowing; in upper / lower, / middle section of the walls)
  - Structural cracking: horizontal (lower / upper / center); vertical (lower / upper / center / coming out of openings / at corners); flexural (wall to wall / mid-wall); diagonal (top to bottom / top to mid-height / bottom to mid-height); or X-shaped (top to bottom / top to mid-height / bottom to mid-height)
  - Detachment of plaster
  - Plaster loss
  - Beetle damage
  - Erosion
  - Moisture damage
  - Presence of vegetation
- Condition of the wood beams, rafters, and quincha frames:
  - Deformation: floors (joists and beams), roofs (rafters, purlins, ridge purlin, collar tie, and arches and ribs), and quincha frames (vertical and diagonal posts)
  - Rotting: floors (joists and beams), roofs (rafters, purlins, ridge purlin, collar tie, and arches and ribs), and quincha frames (vertical and diagonal posts)
  - Termite damage: floors (joists and beams), roofs (rafters, purlins, ridge purlin, collar tie, and arches and ribs), quincha frames (vertical and diagonal posts), and adobe masonry, typically at the base of the façade
- Condition of connections:
  - Corrosion on metal anchors/nails
  - Failure/disconnections: wall-to-wall connections, lintels, floor-to-wall connections, and roof/top-of-wall connections

A complete example of the survey forms is provided in Appendix A.

Earthen Architecture Initiative
Structural Assessment Survey Form – Seismic Retrofitting Project in Peru (SRP)

Universidad Católica Sedes Sapientiae / Pontificia Universidad Católica del Perú / University of Bath / The Getty Conservation Institute

Building: : Iglesia Santiago Apostol KuñoTambo

Address: Comunidad Campesina KuñoTambo, Distrito Rondocan, Provincia Acomayo, Cusco

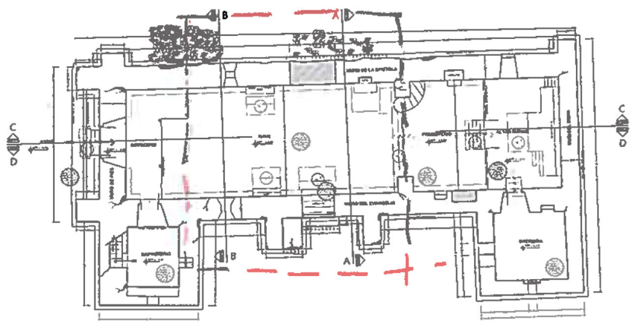
Sector: C

Sector type :

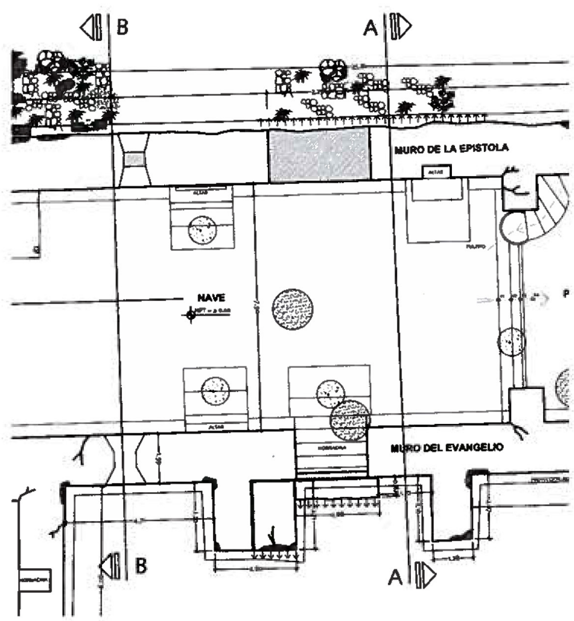
☐ Courtyard / ☐ Tower / ☐ Group of rooms / ☒ Individual Room / ☐ Roof

Level: ☒ First floor / ☐ Second floor / ☐ Third floor

I. Location of sector in building:

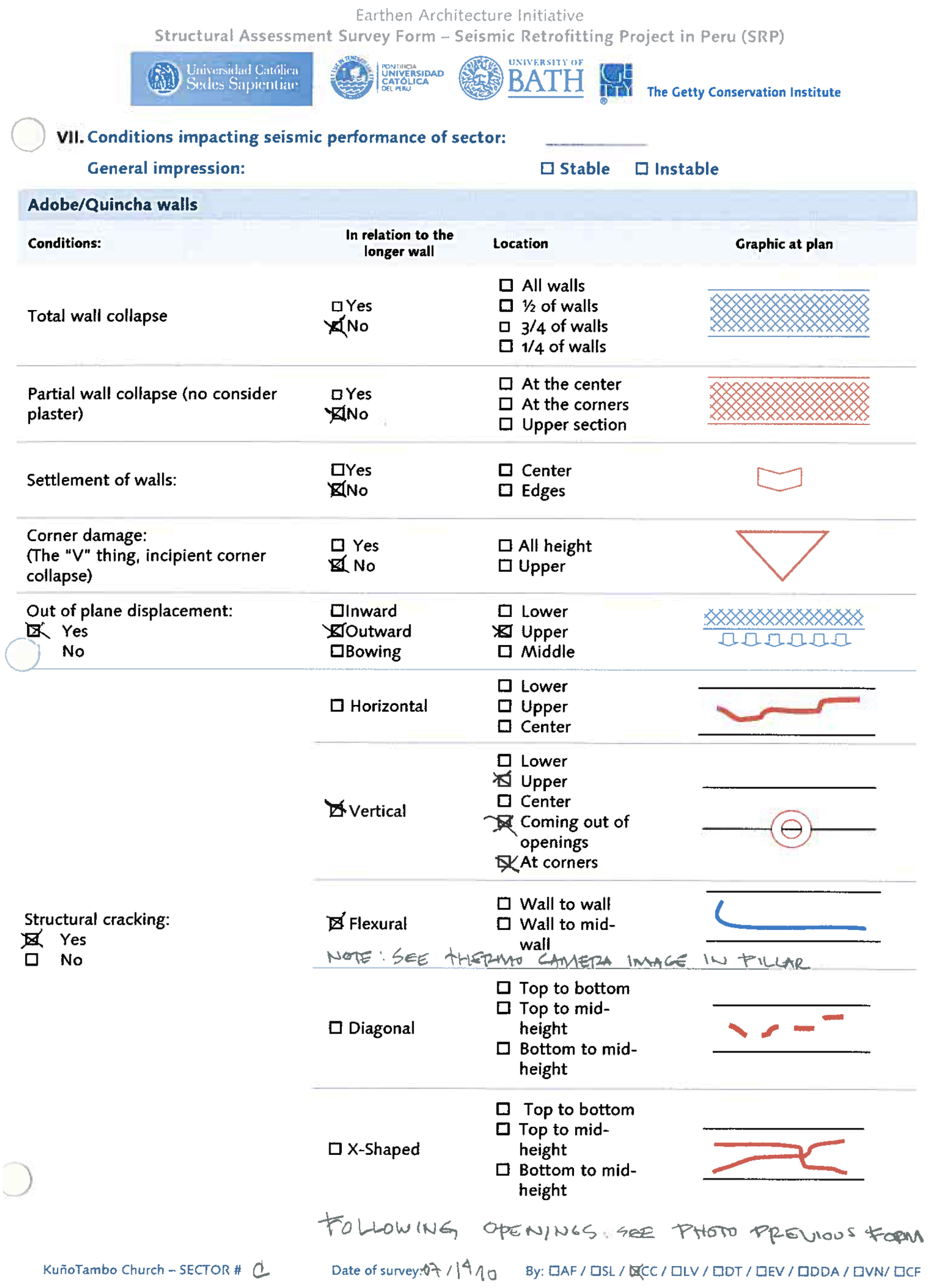


II. Floor plan of sector:



KuñoTambo Church – SECTOR # C   Date of survey: 07/14/10   By: ☐AF / ☐SL / ☒CC / ☐LV / ☐DT / ☐EV / ☐DDA / ☐VN/ ☐CF

FIGURE 2.12
Example of completed sector-by-sector survey form, page 1.



Earthen Architecture Initiative
Structural Assessment Survey Form – Seismic Retrofitting Project in Peru (SRP)

Universidad Católica Sedes Sapientiae · Pontificia Universidad Católica del Perú · University of Bath · The Getty Conservation Institute

VII. Conditions impacting seismic performance of sector:

General impression: ☐ Stable ☐ Instable

Adobe/Quincha walls			
Conditions:	**In relation to the longer wall**	**Location**	**Graphic at plan**
Total wall collapse	☐ Yes ☒ No	☐ All walls ☐ ½ of walls ☐ 3/4 of walls ☐ 1/4 of walls	
Partial wall collapse (no consider plaster)	☐ Yes ☒ No	☐ At the center ☐ At the corners ☐ Upper section	
Settlement of walls:	☐ Yes ☒ No	☐ Center ☐ Edges	
Corner damage: (The "V" thing, incipient corner collapse)	☐ Yes ☒ No	☐ All height ☐ Upper	
Out of plane displacement: ☒ Yes ☐ No	☐ Inward ☒ Outward ☐ Bowing	☐ Lower ☒ Upper ☐ Middle	
Structural cracking: ☒ Yes ☐ No	☐ Horizontal	☐ Lower ☐ Upper ☐ Center	
	☒ Vertical	☐ Lower ☒ Upper ☐ Center ☒ Coming out of openings ☒ At corners	
	☒ Flexural	☐ Wall to wall ☐ Wall to mid-wall	
	NOTE: SEE THERMO CAMERA IMAGE IN PILLAR		
	☐ Diagonal	☐ Top to bottom ☐ Top to mid-height ☐ Bottom to mid-height	
	☐ X-Shaped	☐ Top to bottom ☐ Top to mid-height ☐ Bottom to mid-height	

FOLLOWING OPENINGS: SEE PHOTO PREVIOUS FORM

KuñoTambo Church – SECTOR # C   Date of survey: 07/19/10   By: ☐AF / ☐SL / ☒CC / ☐LV / ☐DT / ☐EV / ☐DDA / ☐VN / ☐CF

FIGURE 2.13
Example of completed sector-by-sector survey sector form, indicating conditions.

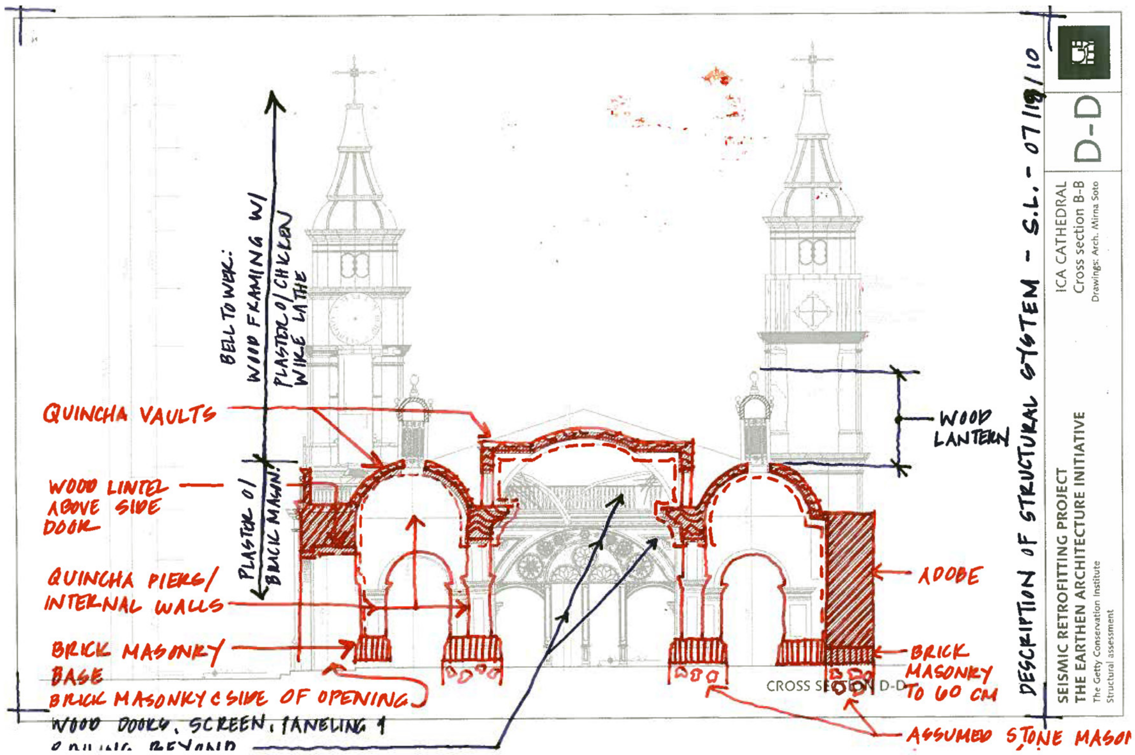


FIGURE 2.14
Example of detailed drawing accompanying survey form, graphically indicating the location of construction materials. Drawing: Sara Lardinois.

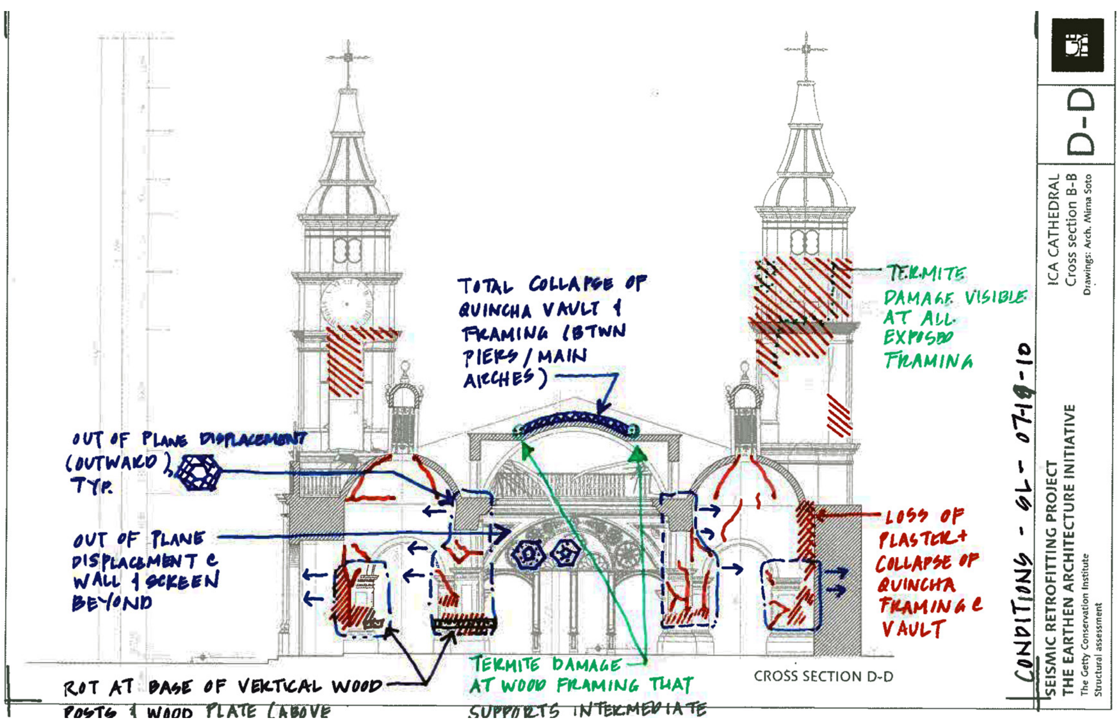


FIGURE 2.15
Example of detailed drawing accompanying survey form, graphically indicating location of observed conditions. Drawing: Sara Lardinois.

2.3.1.2 Nondestructive investigations

The structural assessment of an existing building requires an understanding of materials and connections that are usually not readily apparent through visual analysis. Unless there has been extensive damage to a building, most structural materials will be covered by protective or decorative plasters and finishes. Even when some areas of the building are exposed, it cannot always be assumed that these sections of the building were constructed in the same manner as those that are not exposed, necessitating further investigation. In many cases, this is performed by dismantling portions of the wall, ceiling, or floor, or digging into the foundation of the building which may cause further damage to the building and not be appropriate depending on the nature of the investigation or the importance of the architectural finishes. To avoid this type of damage, nondestructive investigation techniques have been adapted from other fields for use with historic architecture. The use of these techniques on earthen buildings remains a largely unexplored topic, but one which could provide great benefits to the field of earthen architectural conservation. In light of this, several nondestructive assessment methods were evaluated and considered for use with this project; and, of these, infrared photography and thermal imaging were identified for on-site trials.

Infrared photography

Infrared photography is a method of capturing non-visible light waves that reflect off of surfaces. Because it produces images that draw from light waves outside the usual visible range it can be utilized for the detection of materials—particularly on surfaces—that would not normally be seen. In some cases it can illuminate a faint rendering or underpainting that would otherwise go unnoticed. Additionally, some painting materials will effloresce at certain infrared wavelengths and can be detected with the camera. While infrared analysis is not structural in nature, assessment of painted surfaces will inform the planning of interventions, especially if new paintings are found in areas previously thought to be undecorated.

For the on-site trials, a Nikon D70s single-lens reflex camera was used. The internal infrared filters were removed from the camera, and one of three external filters was used:

- “X-Nite CC1”, to block infrared waves and allow for common visible light photography
- “X-Nite 850”, to pass infrared with wave-lengths above 850 nm
- “X-Nite 1000B”, to pass infrared with wave-lengths mostly above 1000 nm

In some cases no filter was attached to the camera, to allow both visible and infrared light to be collected.

The process for infrared photography can be relatively simple, although there are many ways to improve the methodology for more advanced use. Essentially, the camera is mounted on a tripod and remains stationary, without adjusting direction or zoom, while the lenses are exchanged to collect the target light spectra.

During the trials, the infrared images were collected as *.nef files (Nikon’s raw format) and adjusted with Adobe Photoshop’s Camera Raw 5.2 plug-in. The adjustment process can produce very different images from the same file so working standards should be tailored for each specific use. In the SRP trials, each image was adjusted differently to optimize visibility of the paintings.

On the walls of the Church of Kuño Tambo, no new information was revealed by the infrared photography; but, in one area on the west wall by the choir loft, a painted area that had been covered by a thin film of dirt showed more clearly in the infrared images.

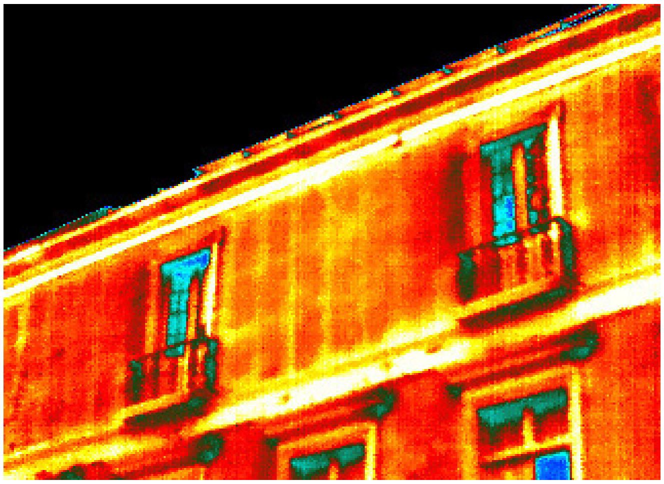
In light of this experience it seems that infrared photography holds potential for investigations of painted walls either in areas where paintings are believed to exist under soiled surfaces or where materials that effloresce may have been used in the painting.

Thermal imaging

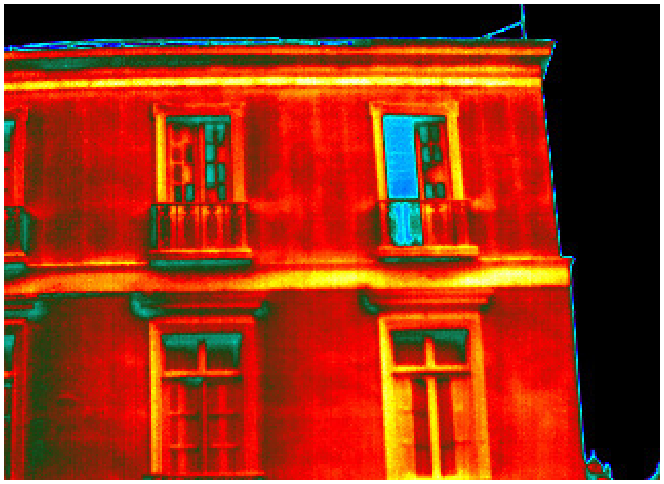
Thermal imaging is a way of visually capturing information on surface temperature. Since the materials within a wall can affect surface temperature, thermal imaging has the potential to reveal where different materials such as wood members, steel plates, brick, or stone have been placed within a building.

For the on-site testing at the four prototype buildings, a FLIR B400 (30 Hz) thermal camera was used. It was set in manual mode so the temperature range could be controlled to improve the legibility of construction materials. The use of the camera was timed to coincide with sunrise in order to take advantage of temperature changes in the building and thus produce the clearest images, especially for exterior elevations. On building interiors, the use of heating devices (such as lights, heat lamps, and wall heaters) to create temperature shifts to illuminate differences in materials was tested; but in the case of the SRP, these artificial heat sources did not significantly improve the legibility of the different materials in the thermal images. Camera settings and environmental conditions which can affect the thermal image—such as emissivity, reflectance, atmospheric temperature, and relative humidity—should be recorded with every image captured to allow transfer of the thermal imaging methods to similar buildings and obtain comparable results.

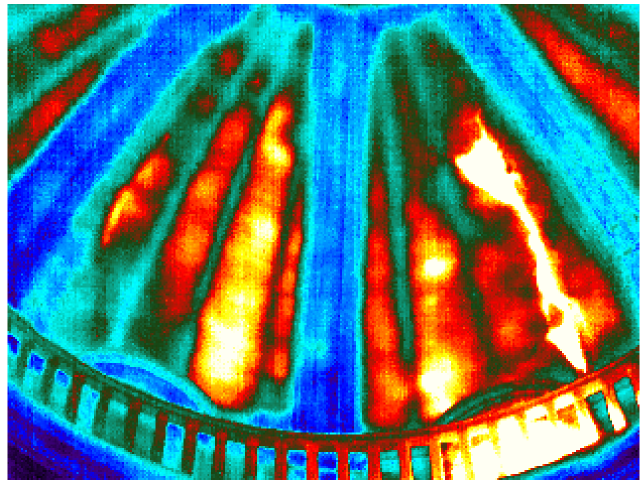
In the SRP on-site testing, thermal imaging proved to be most useful from a structural standpoint for locating the position the quincha posts in the upper stories of the walls at Hotel El Comercio (Figs. 2.16–2.19). Thermal imaging also proved useful in determining the number and placement of wood structural elements in the vaults and domes of the Cathedral of Ica (Figs. 2.20–2.23).



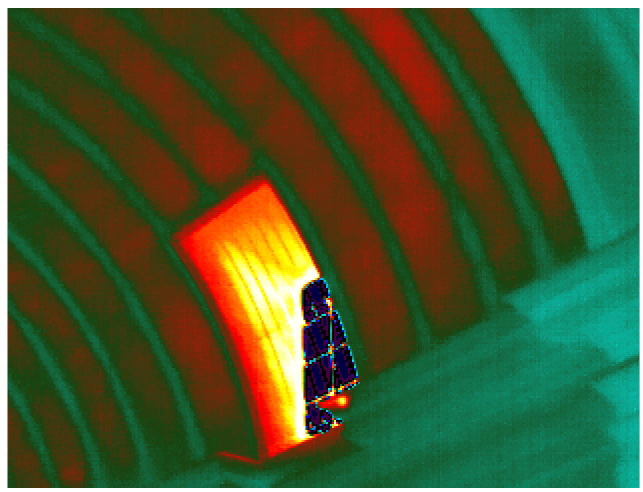
FIGURES 2.16 (LEFT) AND 2.17 (RIGHT)
Northwest façade of Hotel El Comercio: photograph (left) and thermal image (right) of the same sector, indicating the location of the internal wood posts in the third floor quincha walls.
Images: Amila Ferron.



FIGURES 2.18 (LEFT) AND 2.19 (RIGHT)
Northeast façade of Hotel El Comercio: photograph (left) and thermal image (right) of the same sector, indicating the location of the internal wood posts in the third floor quincha walls.
Images: Amila Ferron.



FIGURES 2.20 (LEFT) AND 2.21 (RIGHT)
Dome of the Catheral of Ica: photograph (left) and thermal image (right) of the same sector, indicating the location of the internal wood ribs or arches.
Images: Claudia Cancino.



FIGURES 2.22 (LEFT) AND 2.23 (RIGHT)
Barrel vault over altar at the Cathedral of Ica: photograph (left) and thermal image (right) of the same sector, indicating the location of the internal wood ribs or arches.
Images: Claudia Cancino.

FIGURE 2.24
Prospection in the patio of Hotel El Comercio to determine the foundation configuration.
Image: Mirna Soto, for the GCI.

2.3.1.3 Prospections

To complement the detailed structural survey, annotated detail drawings illustrating structural elements, systems, and connections were provided for the four prototype buildings. These drawings were prepared by opening up select areas the building foundations, wall, and roof structure for further investigation— a process referred to as "prospection."[2] The areas to be opened up were selected by the project partners. In determining which areas of a building to open up, it was necessary to strike a balance between what type of data was desirable to attain and what was feasible to obtain and would not jeopardize the integrity of the site. The work was carried out by GCI consultant Mirna Soto, a Peruvian architect and architectural conservator, and her team of masons (Fig. 2.24). The buildings were opened up during a team field campaign in July 2010; and while the building was open, each prospection area was recorded through field sketches, photographs, and narrated videos. The number and location of prospections did not require the permanent removal of original building materials; and, any necessary repair work was carried out to return the prospection areas to their configuration and appearance prior to the start of work. As the Cathedral of Ica sustained heavy damage during the 2007 earthquake, structural shoring was erected to prevent further damage to the building and to provide a safe working environment for the investigations to be carried out.

The collected data was used to prepare a series of measured drawings, called "prospection drawings." The prospection drawings included:

- Detailed and annotated drawings of the foundation construction techniques, indicating soil stratification for all selected sites. Where feasible, details included cross sections of slopes, internal and external grade levels, and floor levels.
- Isometric annotated drawings illustrating mud brick layouts in the following walls: front façade and lateral wall at the Cathedral of Ica; front façade, lateral walls, and buttresses at the Church of Kuño Tambo; first and second floor walls at Casa Arones; and, first floor walls at Hotel El Comercio. In the case of El Comercio, annotated elevations indicating the layout of the brick surround at first floor openings were also provided (Fig. 2.25).
- Annotated elevations and cross sections of quincha walls at the second and third floors at the corner of sector A and at the façade and internal wall connection in sector B of Hotel El Comercio.
- Isometric drawing and annotated detailed cross section of one pillar at the Cathedral of Ica to show the internal structure, including the connections between wood posts and any extant wall plates at the vault above; and isometric annotated drawing of the central dome and vault structure (Fig. 2.26).
- Isometric drawings and annotated roof plans of typical wood-framed floors and roofs, indicating size, number, and spacing of joists or rafters and collar ties and the position of any extant tie beams.
- Isometric drawings and annotated detailed cross sections illustrating the connections between the main façade and the lateral mud brick walls at the Cathedral of Ica; connections between the façade and lateral walls, façade, and wood balcony and each wall-to-buttress connection at the Church of Kuño Tambo; connections between sectors 1 and 2 at Casa Arones, including roof–wall and wall–ceiling connections; and connections between the

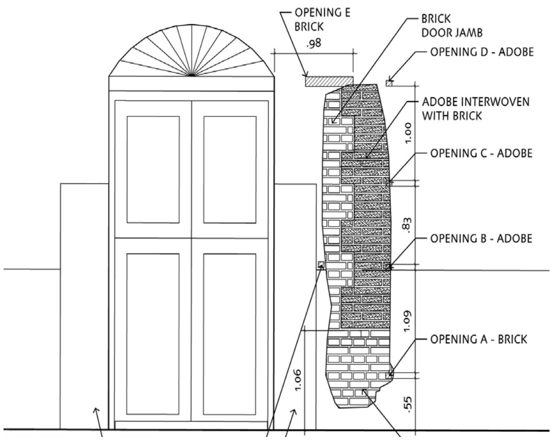


FIGURE 2.25
Example of annotated elevation showing brick layouts at door surrounds, Hotel El Comercio.
Drawing: Mirna Soto, for the GCI.

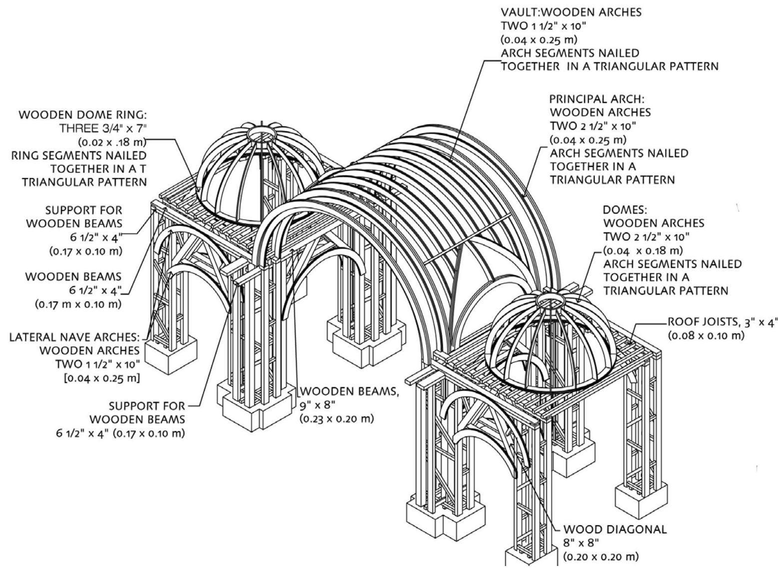


FIGURE 2.26
Example of isometric detail of wood structure at quincha pillars, vaults, and domes of the Cathedral of Ica.
Drawing: Mirna Soto, for the GCI.

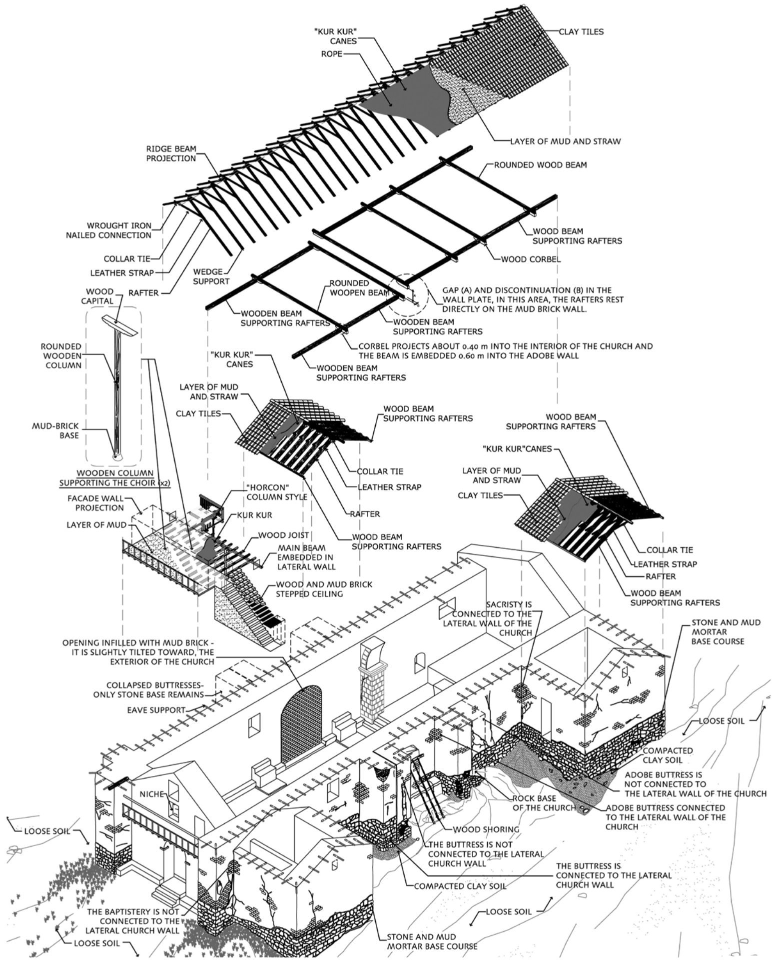


FIGURE 2.27
Example of isometric drawing illustrating the overall structural scheme of the Church of Kuño Tambo.
Drawing: Mirna Soto, for the GCI.

quincha walls and floors, indicating the location of floor joists and quincha posts at Hotel El Comercio.
- Isometric drawings illustrating the overall structural scheme of each building, to provide an overall understanding of the typical construction components (Fig. 2.27).

The full set of prospection drawings prepared for each building is provided in Appendix C. Measurements are typically provided in metric; however, some of the original measurements for wood framing were provided in United States customary or imperial units, as is common practice in Peru. Any original imperial measures have been retained in the both the drawings and report text; and, in such cases metric equivalents have been provided in parentheses following the original measurements.

2.3.2 Basis of preliminary findings

The assessment report also provides preliminary findings on the structural behavior of the prototype buildings. These preliminary findings are based upon the previously-described qualitative investigations. The project team utilized their past experience with historic earthen construction to interpret that data collected through research and observation and develop preliminary ideas on the possible structural behavior of the sites. These preliminary findings will be explored further in the next phases of the project through quantitative methods, including the experimental testing and numerical modeling and seismic analyses. Following the quantitative testing and analyses, the preliminary findings will be revised as necessary and expanded upon to provide a complete diagnosis and evaluation.

2.3.3 Terminology

A number of standard terms have been used to describe the conditions of the prototype buildings. The standard terms, and their associated meanings as defined for the Seismic Retrofitting Project, are as follows:

Poor: A feature is badly deteriorated and immediate corrective measures are necessary to ensure its preservation.

Fair: A feature is beginning to appear to be disturbed or is deteriorating and immediate action is recommended.

Good: A feature exhibits little evidence of deterioration or disturbance and no immediate action is necessary.

Alteration: Any modification performed by man on the original non-structural or structural systems.

Damage: A change of state of a structural or non-structural system, usually caused by natural agents such as earthquakes or floods.

Decay: Long-term processes leading to the deterioration of materials.

Irregularity: A state that is not in accordance with proper construction practices and/or conditions. Irregularities can be caused by construction deficiencies or phenomena occurring during the lifetime of the building.

Notes

1 The colonial period begins with the Spanish foundation of the city of Lima in 1535, includes the period of the Spanish Viceroyalty of Peru (1542–1821), and ends with the declaration of Peruvian independence in 1821 and the establishment of the Republic of Peru.

2 The term "prospection" is derived from the Spanish *prospección*.