APPENDIX 6: PEER REVIEW OF THE STRUCTURAL CONCEPT

Christ Church Cathedral

The Stabilisation and Reinstatement of the Cathedral – Concept Review

Reports Prepared for the Cathedral Working Group by:

- **Holmes Consulting, 18 October 2016**
- **Origin Consultants, October 2016**

Overview of structural concepts (version: A)

for **Mrs Sheila Watson**

(Southern Region General Manager, Heritage New Zealand)

by **Mr Win Clark**

(Structural Engineer, Wellington)

Executive Summary

As requested by Mrs Sheila Watson, I have read the two Concept Review reports and associated drawings. My overview comments are based on these reports and my understanding of the Cathedral building from my engagement by Heritage New Zealand (previously New Zealand Historic Places Trust) to support the staff in Christchurch with structural engineering matters from mid-September 1010. My experience also includes some understanding of the modern engineering approach to the retrofit of stone rubble masonry building used in Europe; Italy in particular.

In my view, the stabilisation and reinstatement concept developed by Holmes Group, and supported by Origin Consultants, provides a sound basis for moving forward to the next stage of developing the required works to retain Christ Church Cathedral. Base isolation of the Cathedral makes sound technical and economic sense for such a building. The base isolation solution will provide a high level of certainty with respect to achieving an acceptable earthquake resistant performance.

Holmes Consulting has noted that the developed scheme for stabilization and reinstatement will require a technical peer review. It is considered that the peer review services are best obtained from overseas. This is due to the limited knowledge and experience currently available in New Zealand for the seismic strengthening techniques available for large stone rubble masonry buildings that will meet world best practice. I strongly recommend that consideration be given to selecting a peer reviewer from one of the leading engineering academics in Italy who are also principals in engineering consultancies that specialize in seismic retrofit of stone rubble masonry buildings.

The areas of comment I have are to do with:

- *Temporary support structures that may be too rigid.*
  During a moderate to major earthquake event, that may occur during the reinstatement works, the stone rubble masonry will tend to distort which could induce damage at the junction of the supported and unsupported elements of stonework. The stone masonry could also pound against the temporary support structure causing damage to the stonework.

- *New rigid structural elements which are fitted into the stone rubble masonry that has different dynamic response characteristics.*
  Homes Consulting have highlighted the issue in their report, but it cannot be overemphasized that significant care is required to ensure:
    - The dynamic response of the stone rubble masonry is well investigated and understood.
    - The dynamic response of any new elements are well understood and appropriate connection provided to the existing stone masonry that ensures stresses are kept low and well distributed. If not properly catered for, significant damage will occur at the interface of new with old elements of the structure.

- *Use of modern stone masonry strengthening techniques to take advantage of the base isolation reduced load intensity in the superstructure.*
  There could well be an opportunity to take advantage of the reduce intensity of the earthquake effects, due to the base isolation, to retain more of the heritage fabric by using various newly developed techniques that enhance the earthquake resistance of the original stone rubble masonry.

I fully support the issues identified in section 3 'Lessons Learned' of the Holmes Consulting report, from their experience on the Arts Centre project. It is imperative that a project management framework be fully developed that allows a collaborative team approach to operate with appropriate flexibility, and which can respond quickly and effectively to conditions found on site as the work progresses.

Introduction

On Wednesday 19 October 2016, Mrs Sheila Watson requested that I provide her with overview engineering comments on the two[1], [2] reports prepared for the Cathedral Working Group by Holmes Consulting and Origin Consultants on The Stabilisation and Reinstatement of the Cathedral – Concept Review, dated October 2016.

On the same day, Resource Co-ordination Partnership Ltd (Mr Marcus Read) sent to me by E-mail the two above reports, and a set of the concept drawings[3] dated 10/10/2016 for The Stabilisation and Reinstatement of the Cathedral prepared by Holmes Consulting.

I have read the two reports and viewed the drawing to gain an understanding of the proposed concept for stabilisation and reinstatement of the Cathedral building. It is on these two reports and the drawings that I have based my comments. It is noted that the reports are essentially of a 'Concept'[4] phase design, sufficient to prepare a 'Rough Order Costing'. It is considered that the design has been advanced into the next phase of 'Preliminary' design to provide a little more information to assist the costing due to the unusual nature of the stabilisation and reinstatement works. However, it should be appreciated that as far as I am aware there is no current detailed assessment of the building condition or testing of materials to determine their mechanical properties. It is assumed that Holmes have relied on information they previously obtained from earlier work, such as the 1999 structural strengthening in the west end of the Aisles and Nave.

At a technical level of structural analysis and assessment it should be clearly appreciated as to how well the assumptions engineers make, with respect to the dynamic behavior of the structure and its materials during an earthquake, fit with the likely performance of the building under review. Our perception of dynamic damping, ductility etc, tend to be influenced by the historic investigations, research and observations over the last 60-years. It is also influenced by the evolution of solutions to meet modern-day develop of infrastructure (bridges) and commercial buildings (multi-storey). In New Zealand these technical developments were greatly influenced by advances in the USA with building design to resist earthquake effects. This was particularly the case in California where commercial building construction was growing to meet society's demands for office/hospital/schools/industrial accommodation, and that would survive severe earthquake events. Therefore the

[1] ChristChurch Cathedral Working Group: The Stabilisation and Reinstatement of the Cathedral – Concept Review prepared by Holmes Consulting, Project 106324.06 version 2.0 dated 18 October 2016

[2] Christchurch Cathedral Proposed Reinstatement: Heritage Report prepared for the Cathedral Working Group by Origin Consultants dated October 2016

[3] Cathedral Working Group, Job No. 106324.05 drawing numbers: 1.01, 1.02, 2.01, 2.02, 2.03, 2.04, 2.05, 2.06, 3.01, 3.02, 4.01, 5.01, 5.02, 5.03, 5.04, 5.05, 5.06, 5.07, 5.08, 5.09, 5.10 & 5.11 dates 10/10/2016

[4] "Design Documentation Guidelines: Structural" prepared by the New Zealand Construction Industry Council dated August 2004

early focus was on understanding the earthquake resistant performance of reinforced concrete frame/shear wall or structural steel frame buildings, and develop construction detailing that would enhance their earthquake resistance[5, 6]. These primary basic concepts were built-on to develop our modern understanding of how buildings withstand earthquakes, develop sophisticated computer-based programs to analysis the dynamically response of buildings, and construction details that provide seismic resistance. However, there is a difficulty when these basic concepts are used to assess and analysis different forms of buildings constructed with different materials. Care is required to ensure the assumptions inherent in the method of analysis is not so significantly out of alignment with the real building characteristics as to make the results of the analysis invalid. It is suggested that with the analysis and structural strengthening of the Cathedral building, considering it's stone rubble masonry construction, that these issues are fully assessed, identified and catered for in the analysis and design method.

Earthquake Resistant Capacity of the Original Cathedral's Building Fabric: Three Wythe Stone Rubble Masonry

Three wythe[7], stone rubble masonry can take many forms, most of which have a poor performance with respect to resisting earthquake effects. The main reason being the individual stone elements of the fabric are not well bonded, therefore, under the dynamic excitation of the earthquake they move independently to become detached from the wall matrix. Also the inner and outer wythe can move away from the core, allowing the rubble of the core to settle which generates a wedging action that further forces the wythes apart. There are other forms of failure such as diagonal shear failure of the wall-piers between window and door openings, and shear dislocation at the corners where adjacent walls meet.

Modern research and testing overseas has identified the generic forms of failure in stone rubble masonry building construction. It is also shown that the earthquake resistance of existing stone rubble masonry walls can be significantly enhanced with various techniques that allow the masonry to distort so that energy is absorbed and loads redistributed to keep stresses low throughout the masonry structure. These techniques are aimed at providing greater binding of the stone matrix and filling voids with specialized grouts, and installing various configurations of transverse (to the wall plane), longitudinal and vertical ties. Many of these interventions lie within the wall profile while retaining the original heritage fabric, and therefore provide a high level of acceptance for heritage buildings.

Obviously the resultant structure does not have the full resilience of a modern structure using modern engineered materials. However, together with base isolation

[5] Blume, J. A., Newmark, N. M., Corning, L. H. (1961) *Design of Multistory Reinforced Concrete Buildings for Earthquake Motions*, Chicago: Portland Cement Association.

[6] Newmark, N. M., Rosenblueth E. (1971) *Fundamentals of Earthquake Engineering*, Englewood Cliffs, New Jersey: Prentice-Hall Inc.

[7] Wythe: a continuous vertical section of brick or stone masonry one unit in thickness. A wythe may be independent of, or interlocked with, the adjoining wythe(s).

there may well be an opportunity to enhance the capacity of the existing fabric to resist earthquake effects, retain a degree of flexibility and damping, without the need to introduce new strengthening elements that are designed to carry the full earthquake loading above the isolation plane. The ability to retain as much of the original heritage fabric as possible should be explored further.

Consideration could be given to overseas experience, research and practice[8, 9] where stone masonry heritage buildings are more prevalent than in New Zealand. In Europe, they have a much longer history of dealing with stone rubble masonry buildings, and large cities populated with such buildings that have been subjected to damaging earthquake effects for centuries. In addition, over the last 15-years there were major research efforts to identify the failure mechanisms inherent in stone rubble masonry during an earthquake, and to identify structural strengthening solutions that enhance the resilience of these structures. Stone rubble masonry buildings that were strengthened using these techniques have withstood major earthquake events with little or no damage[10]. The key messages from this research are:

- Tie the stone rubble masonry together with such techniques as transverse ties through the thickness of the wall, and dowelling the 'L' and 'T' junctions into the body of the adjacent wall.
- Grout the void spaces within the wall fabric with flexible grouts that have high adhesion to the stone masonry.
- Provide ties around the perimeter of the building at floor and roof level.
- Provide floor and roof diapragms tied into the perimeter masonry walls. The diaphragm horizontal load stiffness is tuned to the flexibility of the walls, but inhibits wall failure.

The four arches of the Cathedral nave/transept crossing require reconstruction to allow the four main columns to sway under seismic loading, despite reduced loading due to base isolation. To allow this sway action vertical shear movement will occur up through the centre of the arches[11]. This is generally addressed in the Holmes report. However, it is considered that further analysis is required to determine the distortion of the frames and their stone cladding. Low-damage detail should be considered to allow movement without loss of the stone veneer.

Base Isolation

A primary aspect of the reinstatement is to provide a base isolation system below ground floor level. The objective is to reduce the earthquake loading that would otherwise be generated by the inertia mass of the superstructure, and allows separation of the ground movement from the building. This movement is taken up within the plane of the isolation bearings and sliders.

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8 http://www.niker.eu/

9 http://www.perpetuate.eu/about-us/workpackageslist/

10 Refer APPENDIX 2

11 This vertical shear distortion up through the centre of the arches at a Crossing of a Nave and Transept was clearly demonstrated at the Christchurch Basilica. Refer Photo 1 & 2 of Appendix 3.

The base isolation solution will provide a high-level of certainty with respect to achieving an acceptable earthquake resistant performance. The building superstructure attributes of:

- Heavy weight,
- Large footprint,
- Low height to width ratio,
- Many different element with their own natural period of dynamic response,
- For the building as a whole, a relatively low period of dynamic response,

are suited to an efficient base isolation system that achieves the objective of reducing as much as possible the acceleration due the horizontal earthquake effects. To reduce the peak acceleration is an effective way of protecting the poorly bonded, stone rubble masonry topology of the original construction fabric.

Note, that the earthquake acceleration experience by the building superstructure, above the isolation plane, is significantly reduced, but not eliminated entirely. This is due to the need to limit the width of the moat around the perimeter of the building (moat provided to allow for ground movement relative to the superstructure), and provide some stiffness in the bearing so that the superstructure does not move under normal wind loading etc. Therefore, the superstructure does require capacity to resist horizontal forces, but to a much lesser extent than for a building supported directly on the ground, as well as vertical acceleration from the earthquake effects.

Incompatibility of Original Masonry with New Construction

The reinstatement design shows a mix of various systems and materials to enhance the earthquake resistant capacity of the building superstructure. There is a concern that new structural elements, that are introduce to strengthen the building, will be significantly stiffer than the original building fabric. This has the potential to lead to damage at the interface of the new and old as they respond differently to the earthquake effects. Pounding could be an issue.

Overseas research[12] has shown that great care is required to ensure the dynamic response compatibility of all the various building elements, to minimize damage that may occur in a significant earthquake event. To achieve this, either the elements respond in unison or they are very well tied together to provide an interconnection that will force the members to respond as one structure; this can be very difficult to achieve and may not provide the resilience expected or required. If the whole building is stiffened due to the addition of new structural members, this could increase the dynamic loading within existing stone masonry elements sufficient to cause further damage, particularly for a long duration earthquake event. It may be found that allowing the original fabric to flex under restraint may provide a better solution than introducing new stiff elements that are designed to carry the full earthquake loading.

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12 http://www.reluis.it/CD/ReLUIS-EC8/pdf/18_EC8-ReLUIS.pdf

In the subsequent stages of the Cathedral reinstatement design, detailed analysis will be required to determine the dynamic interaction of these new elements with each other and with the original building fabric. Careful consideration should be applied when designing the construction details for the connection of one element to another. In the existing materials the stress levels must be low and well distributed to minimize damage. Currently there is a real difficulty in determining what these responses would be and their interaction, as little is know of the dynamic characteristics of the original fabric and how the new, possibly stiffer, elements would behave. This suggests that before any further design work is undertaken a programme of investigation is put in place to maximize the understanding of the materials that make up the Cathedral; their form of construction (variations throughout the building), and their dynamic response to earthquake effects.

Until significant further investigation is carried out on the existing building and its fabric, it is not possible to tell with a high level of certainty what the earthquake resistant performance of the building will be. These unknowns have the potential to significantly affect the cost of the works.

With the benefits of base isolation, there may be an opportunity to enhance the capacity of the existing fabric to resist earthquake effects, retain a degree of flexibility and damping, without the need to introduce new strengthening elements that are designed to carry the full earthquake loading. This may provide an opportunity to retain more of the original heritage fabric.

Temporary Securing of Stone Rubble Masonry Buildings

Various temporary support systems are shown in the drawings that include diagonal braces anchored to ground. With these brace structures care is required to ensure the supported section of the masonry building is not so rigidly held that there is a likelihood of damage when adjacent section of the building respond to possible earthquake effects. Consideration should be given to tying the section requiring support back onto the supporting elements of the building so that it does not significantly change the current supporting mechanism, provided these structures have sufficient capacity to contribute adequate support.

Another option that could be considered is to use supporting frames fabricated from 40mm dia galvanized scaffolding tube with clamp connections. The strength and stiffness of these supporting frames can be designed to provide the required strength demand, have a stiffness that allows some flexing of the supported masonry so as to reduce any pounding effect, and allow redistribution of stresses through the masonry. The scaffolding support structures shown in Appendix 1 are to a sophisticated design, but simple to construct using standard elements, easily modified to meet site requirements, and readily dismantled for alternative use when no longer required.

A principle objective of these tubular support frames is to allow the original masonry structure to carry as much of the earthquake design load as possible, with the frames packed and clamped to ensure the masonry does not disintegrate due to the earthquake effects. In this way the support frames are not required to carry the full earthquake inertia load from the masonry.

Peer Review of Cathedral Stabilisation and Reinstatement Concept

New Zealand, in its relatively short history, does not have a large inventory of stone rubble masonry buildings. Those stone rubble masonry buildings we do have, tend to be concentrated in areas where the selection of building materials tended to be biased towards the availability of good building-stone compared to other traditional construction materials. This suggests that in NZ stone masonry skills are limited and concentrated in areas where stone is readily available. Similarly, the structural engineering skills tend to reside in engineering consultancies that have been prepared to undertake, over the years, the limited work available.

To ensure that best practice is provided for the Christ Church Cathedral stabilization and reinstatement it is recommended that a peer reviewer is selected who can bring extensive knowledge and experience in the structural strengthening of large stone rubble masonry buildings, like the Cathedral, to this project.

It is suggested that a large body of this knowledge is contained within the universities of Pavia and Padova, Italy. They have carried out substantial research in the field of large stone rubble masonry buildings subjected to major earthquake effects. The lead researchers and practitioners from these universities have close collaborative ties with both University of Auckland [Professor Jason Ingham (masonry structures)] and the University of Canterbury [Professor Stefano Pampanin (seismic engineering) and Dr Sonia Giovinazzi (Risk Management)]. There are a number of PhD students that are jointly supervised by academics from Italy and New Zealand, working on the seismic behavior and retrofit of masonry (particularly brick masonry) structures[13].

An appropriate peer reviewer for the Christ Church Cathedral project could be selected from the following Italian contacts, or a person with the required skills and experience recommended by the academics working in New Zealand noted above:

- **EUCENTRE, University of Pavia, Italy**
  http://www.eucentre.it/about-eucentre/?lang=en

  http://www.eucentre.it/?lang=en&option=com_content&view=article&id=44%3Aguido-magenes&catid=15&Itemid=192

  Associate Professor Guido Magenes
  http://www.eucentre.it/masonry-structures/human-resources/guido-magenes/?lang=en

[13] http://www.eqc.govt.nz/research/research-papers/1399-Vulnerability-analysis-unreinforced-masonry-churches

- **University of Padova, Dept of Civil, Environmental and Architectural Engineering, Italy**
  http://www.unipd.it/international-highlights/node/72

  Associate Professor Francesca da Porto
  http://www.dicea.unipd.it/en/francesca-da-porto

  Prof. Ing. Claudio Modena
  http://www.domesintheworld.com/wp-content/uploads/2010/06/Modena-Claudio.pdf

  There is an associated private engineering consultancy practice
  Expin SRL (Advanced Structural Control)
  http://www.expin.it/?lang=en

- **Numeria Consulting SRL**
  http://www.numeria-eng.it/

  Alberto Dusi, Director
  Alberto Dusi is a Structural Civil Engineer graduated from the University of Pavia (Italy), He has worked on many EU funded projects, and now currently acts as an expert and advisor to the EC. Alberto has extensive experience with the assessment and structural strenghening of masonry heritage buildings. He was an engineering consultant for more than six months in San Giuliano di Puglia, acting as a consultant for the Municipality and the Italian Civil Protection for the emergency shoring and reconstruction activities. He is author and co-author of more than 40 papers and is lecturer for several university courses on Structural Design of Buildings and Seismic Engineering.

The engineers noted above have extensive experience with research into the earthquake resistant performance of stone rubble masonry buildings, including very large church structures, the development of structural strengthening solutions and the installation of these solutions.

The experience gained from the repair and retrofit of the Art Centre by Holmes Consulting will provide significant benefit for Christ Church Cathedral project. However, care is required to identify the differences in the buildings of the Arts Centre and the size, form and construction topology of the stone rubble masonry that makes up the Cathedral. It is considered that a peer reviewer, with particular experience of stone rubble masonry building and their performance in an active seismic zone, will greatly complement the local knowledge and experience that Holmes Consulting bring to the project.

Conclusion

In my view, the stabilisation and reinstatement concept developed by Holmes Group, and supported by Origin Consultant, provides a sound basis for moving forward to the next stage of developing the required works to retain Christ Church Cathedral. However, it is clear that much further work is required to:

- Provide a greater understanding of the foundation soils and how they will interact with the building during an earthquake event.
- Investigate and determine the engineering characteristics of the stone rubble masonry that makes up a large proportion of Cathedral structure.
- Provide detailed analysis of the building structure and its performance during an earthquake event.
- Review the structural strengthening works to identify optimal solutions that enhance the retention of heritage fabric.
- Review the temporary support structures to ensure they will contribute the performance necessary to provide appropriate support and protect heritage fabric.

Base isolation of the Cathedral makes sound technical and economic sense for such a building. The base isolation solution will provide a high level of certainty with respect to achieving an acceptable earthquake resistant performance.

A peer review is recommended of the stabilisation and reinstatement concept for the Christ Church Cathedral. This review to be carried out using experienced overseas personnel who are well versed in the earthquake resistant performance of large stone rubble masonry buildings, and appropriate structural strengthening solutions that are shown to meet acceptable performance criteria.

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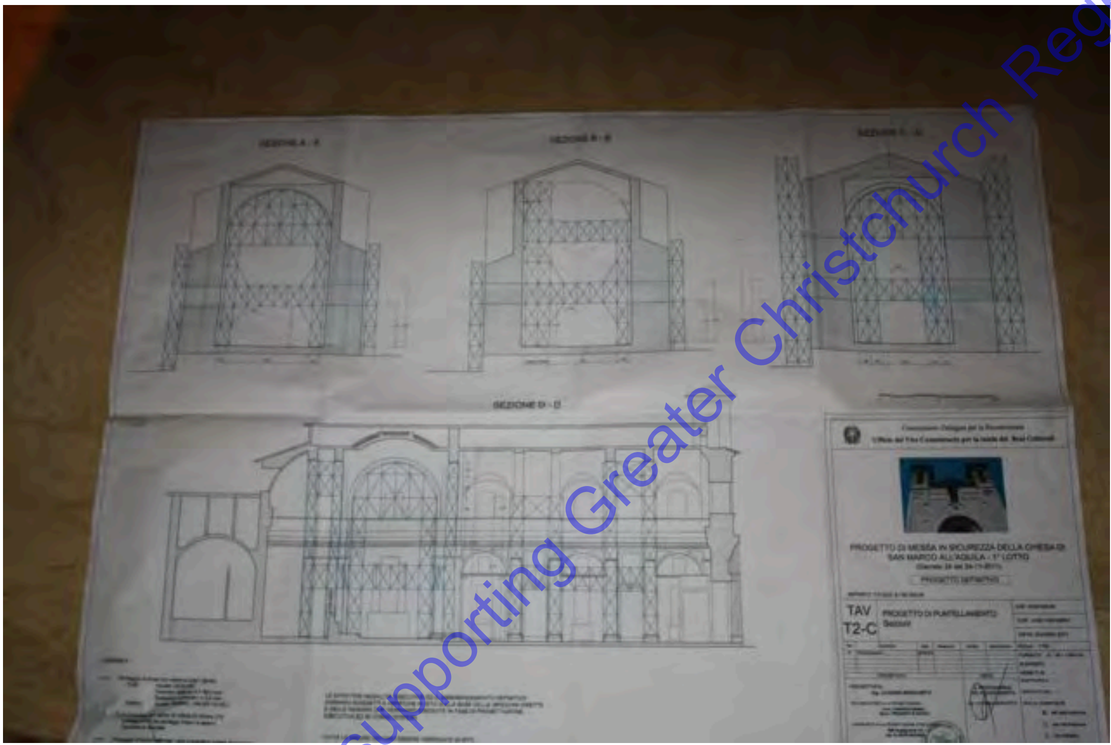
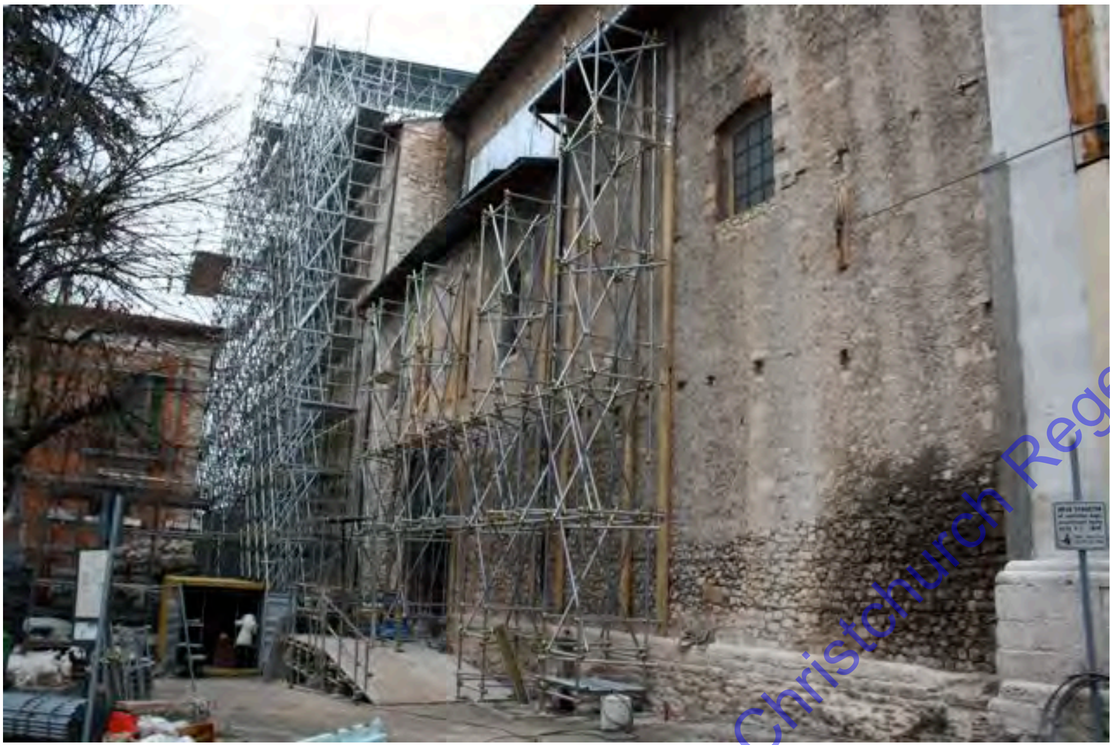
APPENDIX 1

Temporary Securing: Tubular Scaffolding Frames: Photographs
April 2009 Earthquake, L'Aquila, Italy



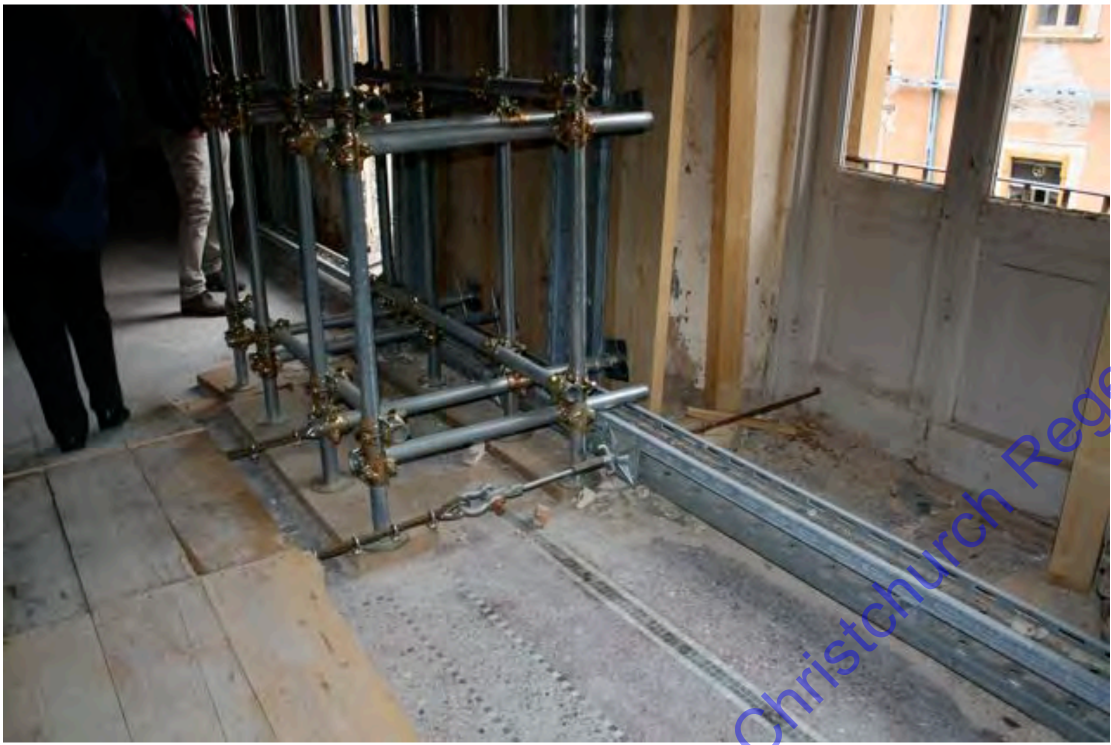
Photograph 1: Scaffold Tube Securing System: Detailed drawings for construction of internal skeleton.



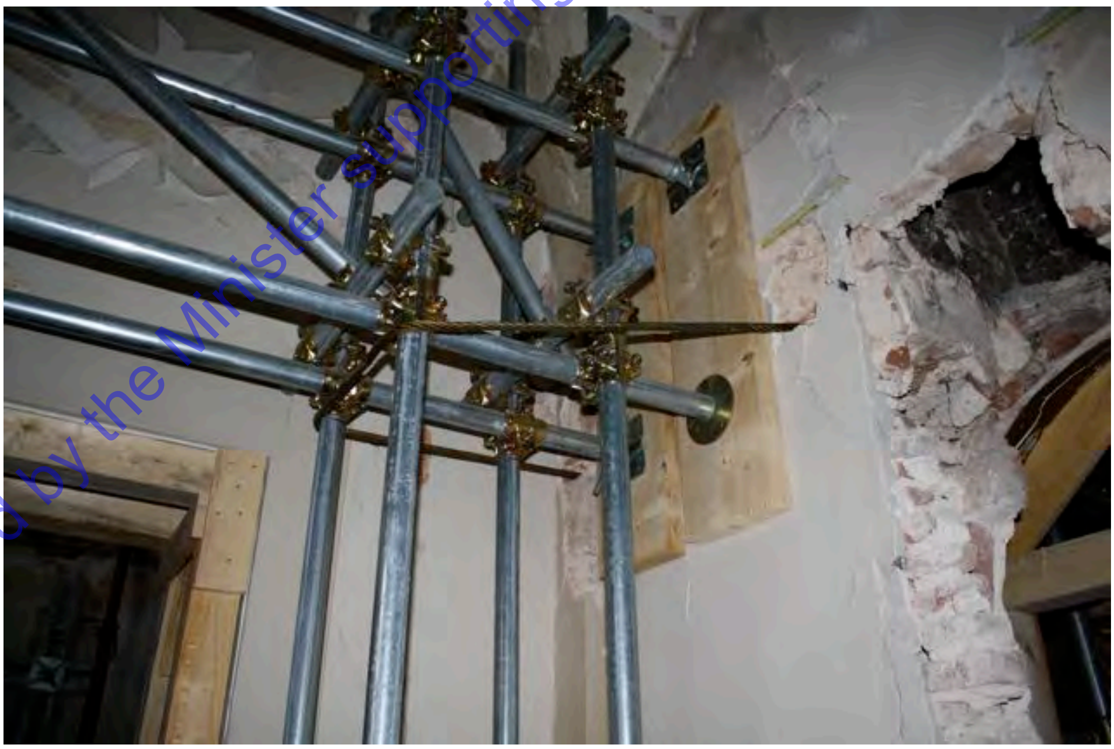
Photograph 2: San Marco's Church: External Skeleton

Photograph 3: San Marco's Church: Internal Skeleton

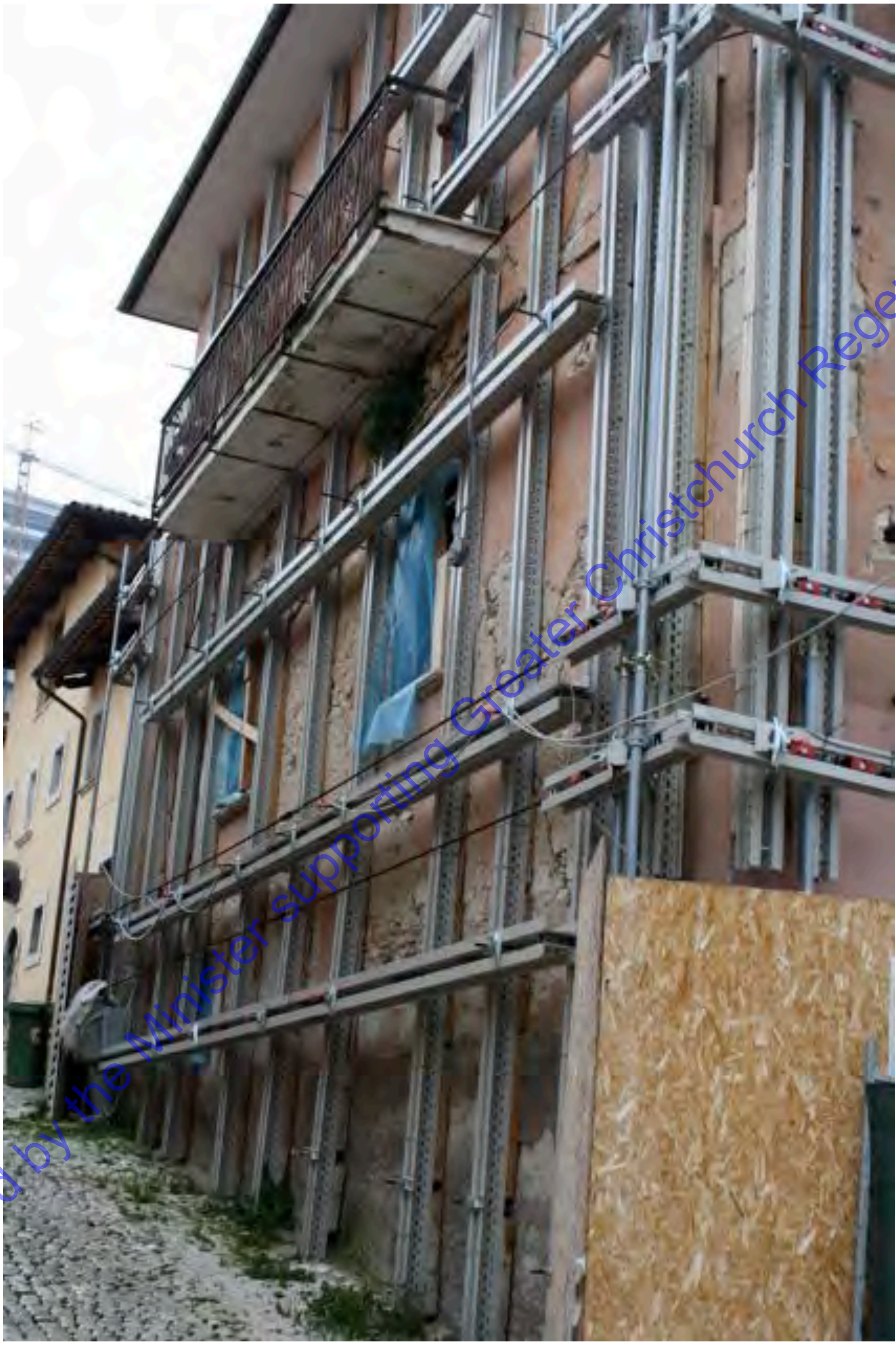
External and Internal Skeleton clamped together with steel wire cables.



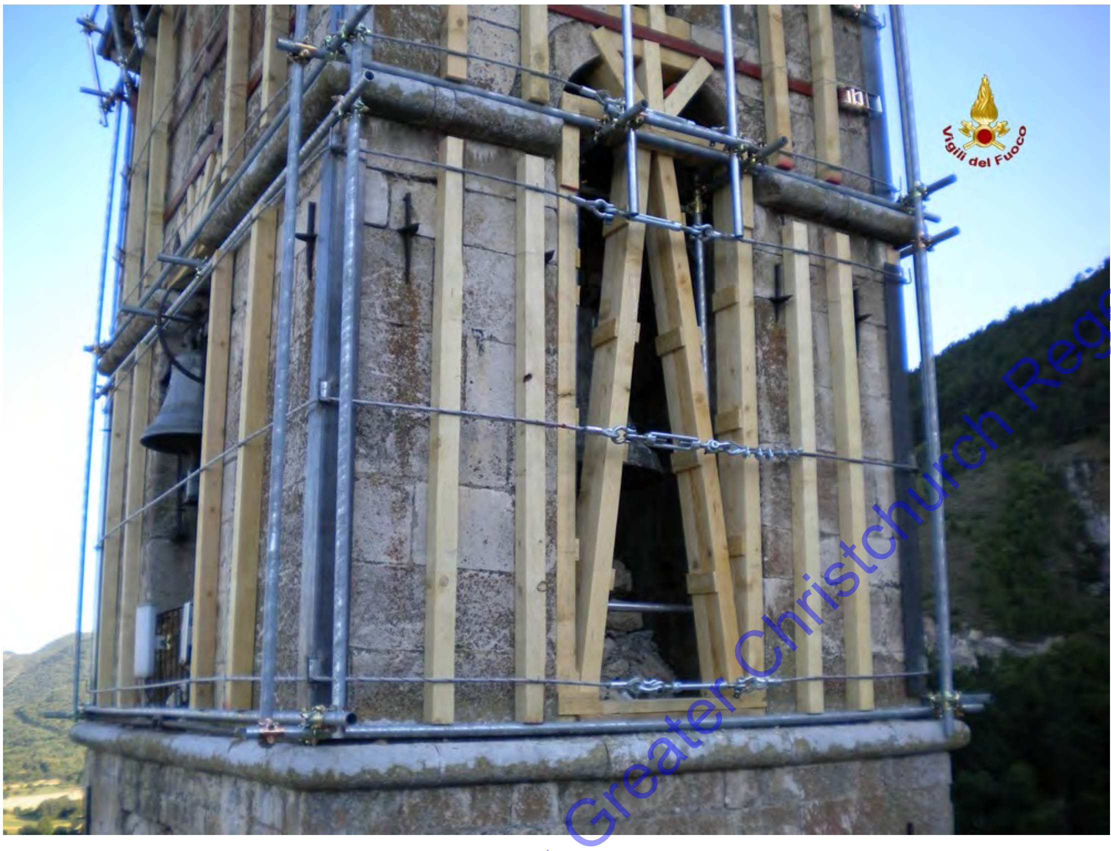
Photograph 4: Masonry clamped between Inner and Outer tubular towers
Note wire ties above floor level clamping building together as a whole.



Photograph 5: Further detail of clamping masonry



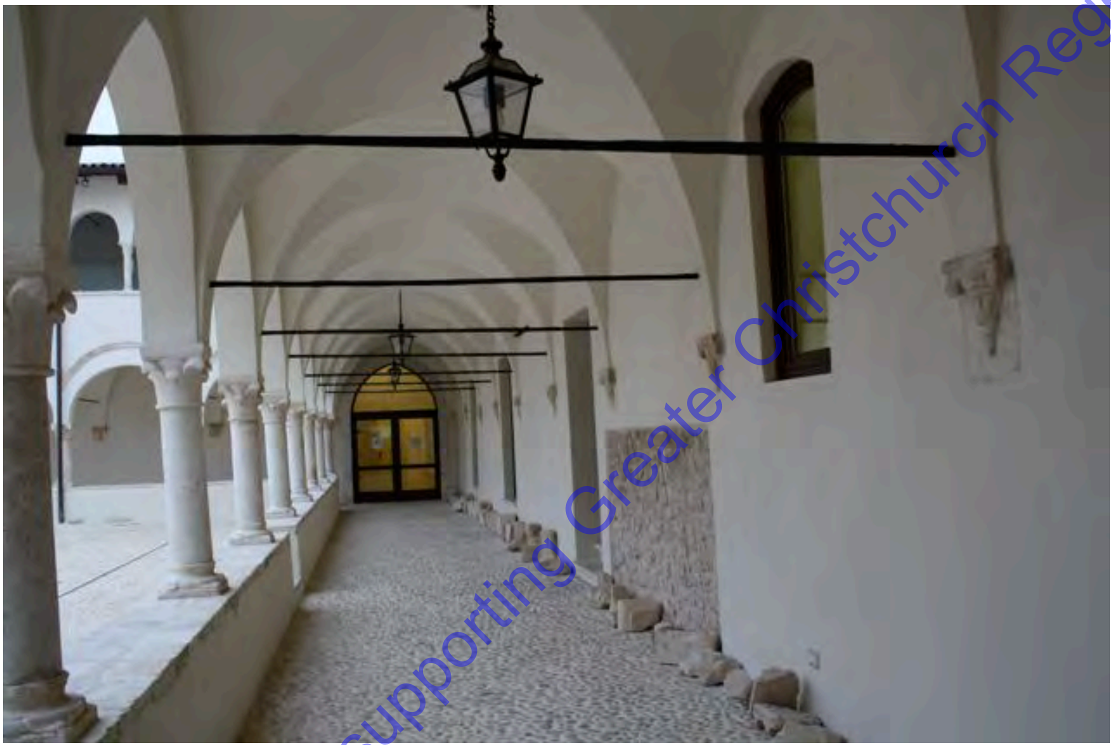
Photograph 6: Ties through building to external frames to clamp masonry building together.



Photograph 7: Tower clamped together with external perimeter ties, and openings strutted with timber framing.

APPENDIX 2

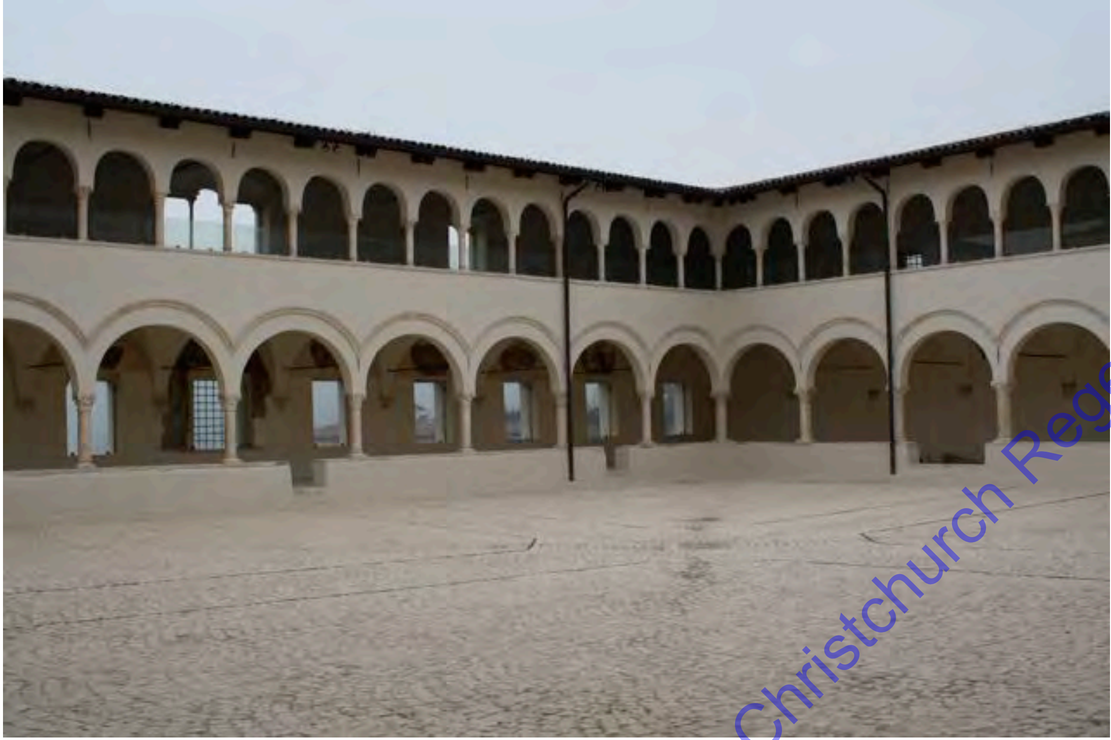
Structural Strengthening of Stone Rubble Masonry Buildings: Photographs
April 2009 Earthquake, L'Aquila, Italy



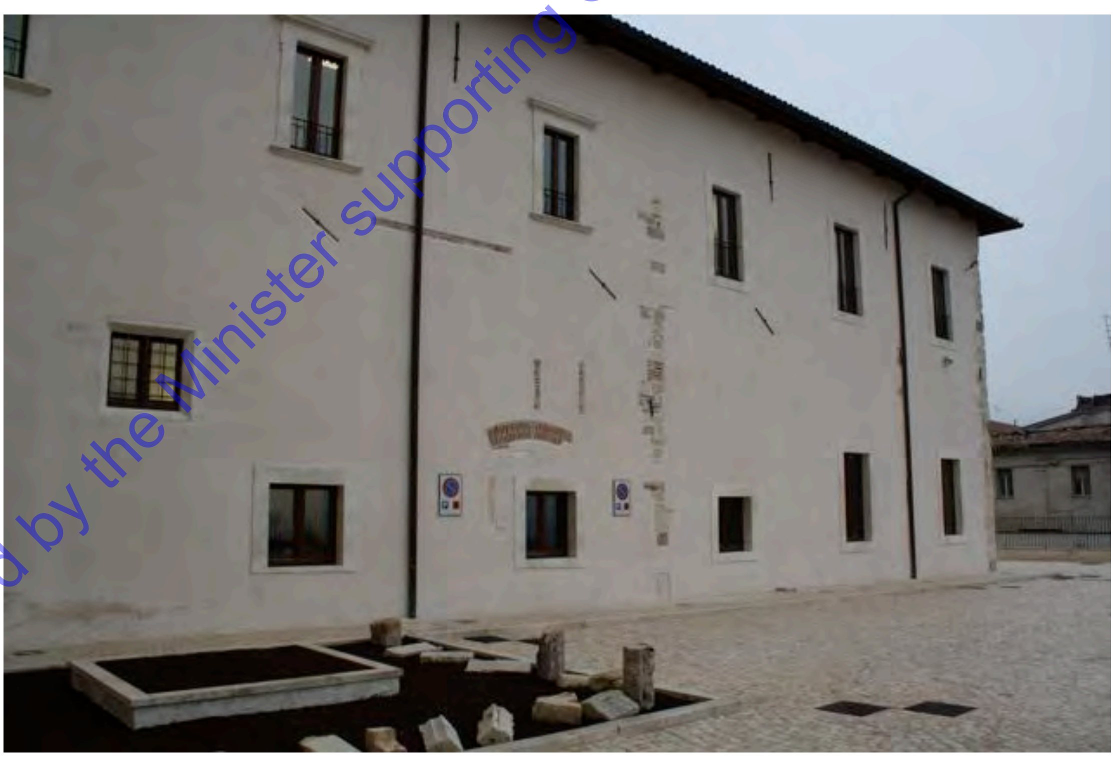
Photograph 1: 13th Century Monastery structural strengthened in 2007

Section of stone rubble masonry left exposed halfway down aisle.

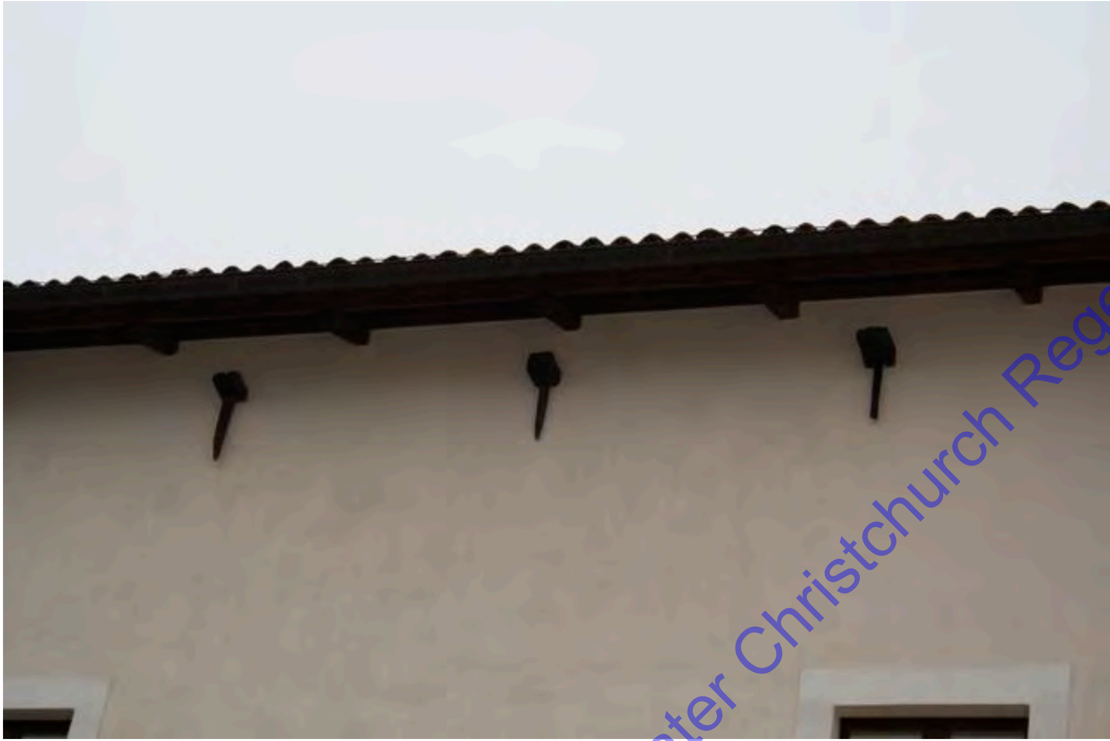
Strengthening including grouting of rubble masonry core and installing transverse ties.



Photograph 2: 13th Century Monastery structural strengthened in 2007



Photograph 3: 13th Century Monastery structural strengthened in 2007

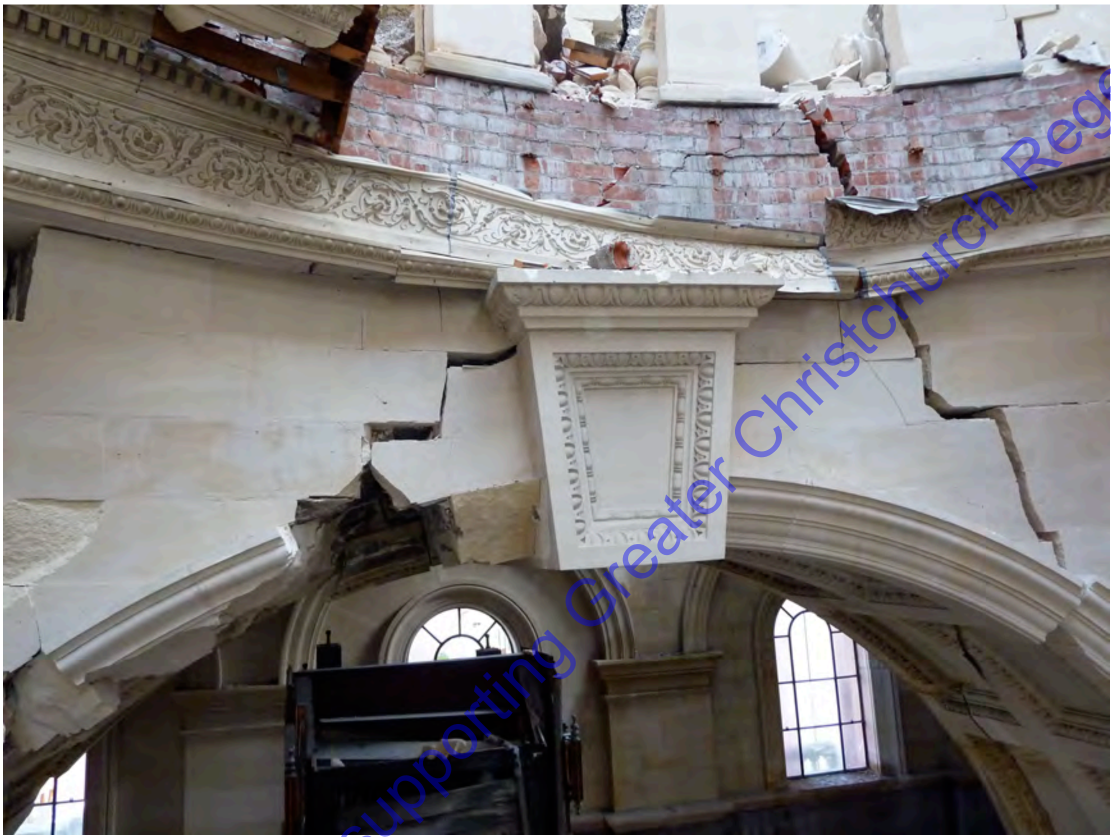


Photograph 4: 13th Century Monastery structural strengthened in 2007

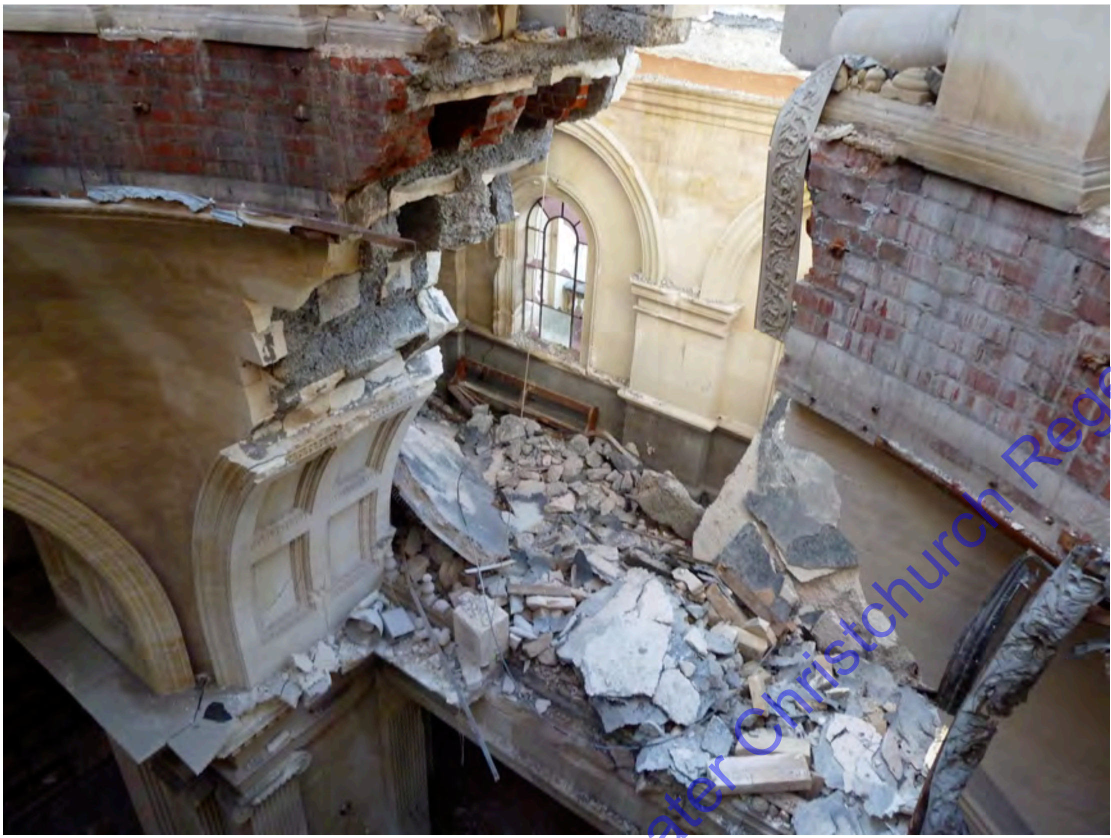
Original construction detail with bottom chord of roof trusses taken through masonry wall and a locking piece inserted to inhibit wall from moving outwards.

APPENDIX 3

Stone Rubble Masonry Buildings: Photographs General



Photograph 1: Christchurch Basilica, earthquake damage due to vertical shear-distortion up through the south arch forming the Crossing of the Nave and Transept. This distortion was due to the rocking in the east-west direction of the four columns supporting the four arches of the Crossing.
Credit: C. Maclean



Photograph 2: Christchurch Basilica, earthquake damage due to vertical shear-distortion up through the north arch forming the Crossing of the Nave and Transept. This distortion was due to the rocking in the east-west direction of the four columns supporting the four arches of the Crossing.
Credit: C. Maclean