Institution: University of Northumbria at Newcastle		
Unit of Assessment: 12 (Engineering)		
Title of case study: Innovative reinforcement techniques protect historical masonry buildings and generate economic benefits for conservation construction companies		
Period when the underpinning research was undertaken: Sept 2013 – Nov 2017		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Marco Corradi	Associate Professor	Sept 2013 - Nov 2017, Feb 2020 - present
Period when the claimed impact occurred: 2015 – 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Historical masonry buildings often need to be reinforced to make them safe for use and protect them from the threats of natural hazards. Unfortunately, many available reinforcement methods are either ineffective or can cause aesthetic damage to the buildings. Dr Marco Corradi at Northumbria University has created innovative reinforcement techniques that are economical, sustainable, easy to fit, and do not impact negatively on the historical value of the buildings. Dr Corradi's research has been adopted by three Italian conservation construction companies and deployed in more than 8,650 reinforcement/intervention projects (2015-2020). This has resulted in a significant improvement in the resistance of heritage buildings to seismic action, providing long-term preservation. These new techniques have also brought significant increases in both turnover and clients for the companies involved, with an overall economic value of approximately EUR30,050,000 (2015-2020), and the creation of 75 full- and part-time jobs. Northumbria University research has also enabled the wider conservation industry to use these techniques through continuing professional development, as well as informing (RILEM and American Concrete Institute) international guidelines.

2. Underpinning research (indicative maximum 500 words)

Historical buildings are often key cultural assets. They provide economic benefits – most notably via tourism – and social benefits, while also contributing to a community's social identity. To protect and preserve their historic and cultural importance for the future, structures built from stone or brick (or other blocks), and bound by mortar, need restoring and reinforcing to make them stable, safe, and secure in the face of earthquakes and the consequences of climate change (e.g., coastal erosion, flooding, etc.), and to endure modern use as residential or commercial buildings. However, ineffective or incorrect retrofitting methods – including the use of materials incompatible with the materials or techniques used to build them originally – have often been applied. To preserve these historical structures, there is a need for innovative and effective engineering solutions that are also economical, sustainable, easy-to-fit to existing structures, and compatible with the existing building materials.

After joining Northumbria in September 2013, Dr Corradi continued his long-term collaboration with Professor Antonio Borri and other colleagues from the University of Perugia, Italy (Corradi left Northumbria in March 2017 and re-joined in February 2020. This case study only reports on impact from research Corradi carried out while at Northumbria). Corradi's methods and techniques on innovative retrofitting and repair techniques for historical masonry are particularly well-suited for reinforcement against seismic action. Corradi's research identifies new methods and materials for historical masonry reinforcement, including natural (stone) and artificial (brick) elements. These methods include Glass Fibre Reinforced Polymer (GFRP) meshes inside a lime mortar and mortar joints that are repointed using a hydraulic lime/mortar and use of high-strength stainless steel cords.

In 2014, in collaboration with Fibre Net (an Italian company that designs, engineers, and manufactures products to reinforce existing buildings), Corradi carried out shear tests (load

parallel to the surface) on 23 masonry panels, before and after reinforcement. In the tests, stone and brick panels were reinforced by means of both jacketing with GFRP mesh inserted inside the lime mortar, and a reinforced repointing of mortar joints using high-strength stainless steel cords [**R1**]. The results showed that masonry reinforced with this intervention increased shear strength between 100-130%, with load capacity also increasing by 60-400%. Variations were found, depending on local conditions, materials, type of construction, etc. The same reinforcement method was also tested in-situ, on panels cut from three historical buildings in Italy. The panels strengthened with the GFRP exhibited more than ten-fold improvement (1060%) in lateral load-carrying capacity when compared to the control panels [**R2**]. A study using numerical modelling also assessed the overall effect on the building over time due to loading, on both the strengthened and unreinforced panels. This modelling confirmed the effectiveness of the intervention and created a tool to support its use in different settings [**R2**]. In 2015, the GFRP reinforcement approach was further investigated by applying it to masonry arches and vaults. Corradi created a new reinforcement technique by combining the traditional Spanish tile vaulting technique (*tabicada*) with composite grids inserted into the mortar coating [**R3**].

The results of [**R1**-**R3**] showed that this specific reinforcement technique (named Reticulatus) is a viable solution to the challenge of strengthening and improving seismic resistance for certain types of historical masonry. In 2016, Corradi and collaborators detailed the 'Reticulatus' reinforcement system and presented new experimental results for four types of cord reinforcement. These used variable materials and diameters for different types of masonry construction [**R4**]. Using materials and financial support from Fibre Net, results demonstrated increases in shear strength of between 15% and 170%. Historical masonry is normally only able to resist compressive forces, but the application of the Reticulatus technique makes masonry resistant to tensile and shear forces, similar to reinforced concrete [**R4**]. These benefits are achieved with limited negative visual impact.

Historically, stone masonry walls were typically made with two 'leaves', i.e., inner and outer walls. A strong vertical load over time, or horizontal load via earthquake or flooding, can result in damage. In 2015, Bossong (an Italian company) worked with Corradi on the problem of weak connection between wall 'leaves' in old buildings. Corradi developed methods to strengthen the connections between weakly-connected wall leaves using steel rods inserted in a grouted fabric sleeve. Tests conducted on site and in the laboratory showed a 50-100% improvement achieved by applying transverse connectors to resisting out-of-plane action, or to rocking produced by, for example, soil pressure, extreme wind, or earthquakes [**R5**].

3. References to the research (indicative maximum of six references)

R1. Borri, A*., Castori, G.*, **Marco Corradi**, and Sisti, R.* (**2014**) 'Masonry wall panels with GFRP and steel-cord strengthening subjected to cyclic shear: An experimental study' *Construction and Building Materials* **56**: 63-73 https://doi.org/10.1016/j.conbuildmat.2014.01.056

R2. **Marco Corradi**, Borri, A*., Castori, G.*, and Sisti, R.* (**2014**) 'Shear strengthening of wall panels through jacketing with cement mortar reinforced by GFRP grids' *Journal of Composites, part B* **64**: 33-42 https://doi.org/10.1016/j.compositesb.2014.03.022

R3. Borri, A*., Castori, G.*, and **Marco Corradi** (**2015**) 'Behavior of thin masonry arches repaired using composite materials' *Journal of Composites, part B* **87**: 311-321 https://doi.org/10.1016/j.compositesb.2015.09.008

R4. **Marco Corradi**, Borri, A. *, Castori, G.*, and Sisti, R.* (**2016**) 'The Reticulatus method for shear strengthening of fair-faced masonry' *Bulletin of Earthquake Engineering* **14**: 3547–3571 https://doi.org/10.1007/s10518-016-0006-5

R5. Marco Corradi, Borri, A*., Poverello, E.*, and Castori, G.* (**2017**) 'The use of transverse connectors as reinforcement of multi-leaf walls' *Materials and Structures* **50** (2): 1-14 https://doi.org/10.1617/s11527-016-0977-3

*University of Perugia
Borri (now retired) was key contact with the businesses, Dr Corradi was the project coordinator and leader of all experimental activity.

4. Details of the impact (indicative maximum 750 words)

After the 1997-98 Umbria earthquakes, which caused a significant loss of cultural heritage in Italy, it became clear that new techniques and methods were needed to preserve and maintain the safety of historical buildings. Northumbria's research has introduced new techniques which meet the demands of conservation organisations and landlords in terms of aesthetics and has resulted in preservation and improved safety of historical buildings. It has also brought economic benefits to conservation engineering companies. ICOMOS (International Council on Monuments and Sites) sets stringent conservation requirements for removability of the materials used for reinforcement. Corradi's interventions offer new economic opportunities for construction companies as the new approaches and products meet these requirements to be reversible, require minimal intervention, and are sustainable.

4.1 Impacts on commerce and the economy – Fibre Net
Fibre Net is an Italian company that designs, engineers, and manufactures materials and systems to reinforce existing buildings and infrastructures for clients in 30 countries. Since 2014, Corradi and collaborators worked with Fibre Net on the Reticulatus method [**R4**], now commercialised under the brand name *RETICOLA* [**E1**, **E2**]. Between 2015 and 2020, the *RETICOLA* product was used by Fibre Net in more than 150 projects, equating to an economic value of **EUR1,650,000** for Fibre Net [**E1**].

Fibre Net also uses other retrofit methods developed by Corradi, including: (i) rigid GFRP meshes [**R2**, **R4**] used in their *Ri-Struttura* and *C-Matrix* products; and (ii) composite-reinforced masonry ring-beams [**R2**, **R3**] for avoiding out-of-plane collapse of load bearing walls. Between 2015 and 2020, Fibre Net adopted and implemented these methods in approximately 8,500 projects, with an economic value estimated at **EUR27,000,000** [**E1**]. The importance of Corradi's research is articulated by the Fibre Net CEO, who states, *'Professor Corradi's advice, the results of his studies, and our joint experimental activities both at the laboratory and on-site were critical and important to us. Thanks to this, it was possible to improve our products, to focus on some limitations of the proposed retrofitting methods, to find solutions, and to acquire knowledge'* [**E1**].

The Fibre Net CEO also stated that the collaboration with Corradi contributed significantly to the development of the company. Turnover almost trebled from EUR5,210,000 in 2015 to EUR13,550,000 in 2019 (an increase of EUR8,340,000 or, equivalently, an increase of 260% compared to the 2015 value). The number of new clients also increased, by 67%, between 2015 and 2020. In addition, the company's international influence also grew such that it now sells its products in new countries [**E1**]. In addition, the introduction of Corradi's methods led to the company creating an additional 75 full- and part-time jobs (headcount: 75) [**E1**].

4.2 Impacts on commerce and the economy – Bossong
Bossong is an Italian company that produces fixing systems for the construction industry. In 2015, Bossong adopted Corradi's work on improving the connection between historical wall leaves using a fixing system [**R5**, **E3**]. Bossong has now deployed this approach to provide a solution to structural problems of historical buildings [**E3**]. The head of Bossong's Strengthening Department *('Area consolidamento'* in Italian) confirmed: *'Professor Corradi, from Northumbria University, has been instrumental in making this possible. He not only advised us where fixing systems could find an application in conservation engineering, but also proposed, studied, and tested a set of technical solutions'* [**E3**]. The value to Bossong of the structural interventions that

use Corradi's methods amounted to an estimated **EUR1,000,000** between 2015 and 2020, and 30% of Bossong's new client base was attracted specifically to deploy this method [**E3**].

4.3 Impacts on commerce and the economy – Kimia

Kimia is an Italian company supplying retrofit systems for the construction world. The results of Corradi's research [**R4**] were used by Kimia in 2016 to commercialise the Reticulatus method under the brand name *Kimisteel*. Kimia worked with Corradi to develop this new product. Building on the advantages of Reticulatus, this product uses composite grids inserted into the mortar coating [**E4**]. The methods were used by Kimia in more than 40 projects between 2016 and 2019 [**E5**]. The Technical Office Manager at Kimia stated: *'Retrofitting heritage masonry structures with advanced materials has become a very important topic of research and development in the sector, and Kimia has been quick to respond to fill this gap. It would have been difficult for Kimia to develop its commercial activities in this area without the collaboration with Prof. Corradi… in the area of retrofit and repair of masonry structures, the value of the output generated by Kimia increased 5% between 2016 and 2019… The overall economic value of these projects is estimated to be **EUR400,000**… We have also seen a 3% increase in clients between these dates due to the new interventions we are able to offer'* [**E5**].

4.4 Enabling preservation and safety of historic buildings

Northumbria University research [**R1**-**R5**], via products made by Fibre Net, Bossong, and Kimia, has been deployed on multiple historic and culturally important buildings, preserving them for future generations and preventing the need for resources and energy to be used for new buildings. These include:

- Fibre Net's *RETICOLA* product has been used on several historic buildings [**E1**], including: the mediaeval tower *Pico della Mirandola* (Modena, Italy, intervention in 2018, a cultural icon that belonged to the Pico family, who reigned over Mirandola from 1311 to 1711) [**E1**]; and Castello di Compiano (Reggio Emilia, Italy, intervention in 2015-2016), where *RETICOLA* was used to improve the resistance of the north tower to earthquakes by 82% [**E1**; **E6A**, p3]
- Fibre Net's *Ri-Struttura* and *C-Matrix* products have been used to improve seismic resistance for listed buildings, palaces and villas, ordinary residences, and educational buildings. For example, *Ri-Struttura* was used at two schools, one for 230 pupils in Villaverla (Italy, intervention in 2016) [**E6B**, p5] and another in Riccione (Italy, intervention in 2018) [**E6C**, p8], to improve their resistance to seismic action. The Riccione school occupies a culturally valuable building built in the early 1900s and the intervention has resulted in a 60% seismic improvement of the building, making it safer and more functional [**E1**; **E6C**, p8]
- Bossong products, underpinned by Corradi's research, have been deployed on Palazzo Ardinghelli (built in 1743 and considered one of the greatest examples of the Baroque in L'Aquila, Italy) and the aggregate around L'Aquila Cathedral [**E3**]
- Kimia products, underpinned by Corradi's research, have been used on the Castle of Normans (Ginosa, Italy, a building dating back to the year 1080, intervention in 2017) [**E5**]

4.5 Developing international capacity to improve building conservation

Fibre Net organises Continuing Personal Development (CPD) training for engineers and architects in Italy to detail the various methods of design, installation, and application of the retrofitting solutions (including those developed as a result of Corradi's research). This CPD forms part of the accreditation of engineers and architects in Italy. Between 2015 and 2019, more than 150 training courses in over 80 Italian locations have been delivered by Fibre Net staff, typically attended by 50-100 professionals each time [**E1**] (total 7,500-15,000 professionals). Fibre Net uses these CPD sessions to explain and propose its own retrofitting solutions, including the *RETICOLA* product, based on Corradi's research [**R4**]. Fibre Net's CEO explains: '[RETICOLA products] *always receive very high interest and attention in the professional community and regularly lead to future clients and projects. Approximately 35% of our new clients are as a result of new methods and advanced material recommendations, studied within the collaboration with Professor Corradi, and given by professionals who have received our CPD*' [**E1**].

Corradi's work has also informed international guidelines that advise construction practitioners on how to deploy techniques to preserve and make safe, historical buildings. In construction, international professional bodies promote sustainable and safe construction, with improved performance and cost benefits. They rely on scientific cooperation to produce guidelines to improve construction practices used by structural engineers, conservation engineers, conservation agencies, and architects across the world. As a result of his expertise in historical masonry reinforcement, Corradi was invited to sit on the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM)'s Technical Committee (TC) 250-CSM: *Composites for sustainable strengthening of masonry*. Corradi's research contributed towards a publication containing the GFRP recommendations and guidelines of RILEM TC 250-CSM, *'Glass fabric reinforced cementitious matrix: Tensile properties and bond performance on masonry substrate'* published in 2017 [**E7**, **E8**]. The Chair of the TC 250-CSM committee states: *'I can really state that the participation of Professor Corradi to this Technical Committee was important and fundamental … the activities of the Technical Committee 250-CSM can be regarded as a fundamental step for the industry working and/or with the intention to enter the market of masonry retrofit and seismic-reinforcement'* [**E7**].

In 2016, the decision was made to harmonise the US and European guidelines on the topic, by forming a joint American Concrete Institute (ACI)-RILEM committee. Corradi contributed as co-author towards these joint US-European guidelines, published in 2020: '*Guide to design and construction of externally bonded Fabric-Reinforced Cementitious Matrix (FRCM) and Steel-Reinforced Grout (SRG) systems for repair and strengthening masonry structures'* [**E7**, **E9**]. These are the first ACI-RILEM guidelines that recommend and detail the use of GFRP for retrofit of historical buildings.

5. Sources to corroborate the impact (indicative maximum of 10 references)

Ref.	Source of corroboration	Link to claimed impact
E1	Testimonial - Cecilia Zampa, CEO, Fibre Net	Confirms economic impact of Reticulatus method and CPD training on Fibre Net
E2	Website page for Fibre Net's RETICOLA product	Confirms Fibre Net's *RETICOLA* product
E3	Testimonial - Elena Poverello, Strengthening Department (from 2001-2016), Bossong	Confirms economic impact of research for Bossong
E4	Website page for Kimia's Kimisteel product	Confirms Kimia's Kimisteel product
E5	Testimonial - Stefano Agnetti, Technical Office Manager, Kimia	Confirms economic impact of Dr Corradi's research for Kimia
E6	Intervention Case Studies: A) *Castello di Compiano*, B) Primary school in Villaverla, C) Primary school in Riccione (from Fibre Net website, translated by Google from Italian to English, accessed 22/11/20)	Confirms use of *RETICOLA* and *Ri-Struttura* methods in Fibre Net projects with improvements to buildings
E7	Testimonial - Professor Gianmarco de Felice, Chair of Committee TC250-CSM	Confirms Dr Corradi's invitation to the committee and guideline contributions
E8	Leone, M., Aiello, M.A., Balsamo, A., Carozzi, F.G., Ceroni, F., **Marco Corradi**, et al. (**2017**) 'Glass fabric reinforced cementitious matrix: Tensile properties and bond performance on masonry substrate' *Journal of Composites, part B* **127**(15): 196-214, DOI: 10.1016/j.compositesb.2017.06.028	Publication containing the GFRP recommendations and guidelines of RILEM TC 250-CSM committee
E9	ACI 549.6R-20 (**2020**) 'Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix (FRCM) and Steel-Reinforced Grout (SRG) Systems for Repair and Strengthening Masonry Structures'	Output from involvement with joint ACI-RILEM guidelines. Dr Corradi listed in subcommittee