Life-Cycle Analysis of Incremental Seismic Retrofitting of Traditional Constructions in Nepal

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Abstract

In the last 2015 Nepal earthquake, over one million buildings were destroyed or damaged, of which more than 50% were traditional stone in mud mortar (SMM) unreinforced masonry (URM) constructions. Empirical evidence from several geographical contexts has shown that URMs have minimal seismic-resistant features. However, adequate retrofitting interventions can substantially increase their seismic performance. The economic cost of retrofitting remains an issue and often prevents building owners and investors from retrofitting their buildings in advance of the next earthquake. This paper investigates the potential for utilizing incremental retrofitting strategies in Nepal, to allow owners to retrofit their buildings in a gradual and cost-effective way. Two main retrofitting approaches for SMMs are broken down into phases, each of which is analysed to quantify the structural improvement to the building. A probabilistic cost-benefit analysis of each phase is carried out to quantify the return on investment of seismic enhancement in Nepal. Results indicate that retrofitting is a financially advantageous investment since the reduction in future earthquake-induced loss largely exceeds the upfront cost of the intervention. Additionally, the incremental approach allows more flexibility in allocating resources and could increase the appeal of retrofitting as a risk mitigation measure.

Keywords: *retrofitting, incremental, stone masonry mud mortar, cost-benefit analysis*

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1. Introduction

Seismic retrofitting is considered one of the most effective techniques for earthquake risk reduction. Past seismic events in Nepal and worldwide have shown that retrofitted constructions are not only safer for the occupants but also less prone to damage (e.g. Sorrentino and Cattari 2019). In an earthquake, the majority of the economic loss comes from physical damage (e.g. Guettiche et al. 2017). Therefore, the implementation of retrofitting interventions at scale can limit disproportionate impacts on the economy when a disaster strikes. This is particularly valid for seismically active regions where traditional non-engineered unreinforced masonry (URM) constructions represent the vast majority of the total building stock. Empirical evidence has shown that URMs are characterized by numerous structural deficiencies that negatively affects their seismic response. To name a few: low mechanical properties of masonry material, poor construction quality, lack of wall-to-wall/wall-to-floor connections, absence of seismic detailing (e.g. Benedetti et al. 1998). In Nepal, where more than 60% of the inventory is constituted by URMs (Central Bureau of Statistics 2011), the average annual loss of the residential portfolio estimated by the Global Earthquake Model (Pagani et al. 2014) is about 400 Million USD. This is roughly 0.36% of the asset replacement cost, consistently higher than the average 0.11% of the world's top sixteen earthquake affected countries.

Despite this, there are still barriers to seismic retrofitting (Nuti and Vanzi 2003). First, structural interventions represent an important upfront investment for building owners, that can be up to 60% of the replacement cost of the building (e.g. Liel and Deierlein 2013). Second, such interventions are usually invasive (involve the removal of non-structural components and finishing) and disruptive (require temporary relocation of the building occupants). Third, building owners and investors are usually uncertain about the benefit of retrofitting that is projected into a distant and unforeseeable future. That said, the financial cost of disasters is eventually paid by Governments that have to cope with disproportionate losses given the large number of unretrofitted buildings. Therefore, from a regulator perspective, it is crucial to incentivize retrofitting *before* a major earthquake strikes.

Mechanisms to incentivize seismic retrofitting have been discussed since the nineties (Federal Emergency Management Agency 1994) and nowadays are an integral part of disaster risk reduction programs in several countries. A common characteristic of these policies is that older buildings are not required to perform at the same level of new constructions. On the contrary, partial retrofitting interventions are allowed, aimed at an improvement of the original capacity of the structure. In this way, the limited available resources for risk mitigation can be distributed over a larger number of constructions to homogeneously increase the resilience of the building stock. For instance, with the California Residential Mitigation Program (California Earthquake Authority 2011), homeowners of vulnerable houses constructed before 1979 can apply for a grant of 3,000 USD to bolt down the building and brace the cripple walls with plywood, to prevent collapse or sliding off its foundation. New Zealand is also following an approach based on partial retrofitting. The Building Amendment Act 2016 requires commercial building owners to strengthen their properties up to at least 34% of the most recent building standard and provides incentives for historical listed buildings to be retrofitted at 34% of the building code (Filippova and Noy 2020). One of the most innovative seismic retrofitting policy was released by the Italian Government in 2017. The *Sisma Bonus* Act (Ministero delle Infrastrutture e dei Trasporti 2017) supports residential and commercial building owners to invest in the seismic enhancement of their properties thanks to tax deductions of up to 85% of the total retrofitting cost. To access the tax relief, the owner must file a structural report that quantifies the seismic performance of the building before and after the intervention. In detail, the performance is expressed in the form of eight risk classes from G to A+, where A/A+ corresponds to the performance of a new building. A tax deduction of 70-75% applies when the retrofit results in an improvement of one class; the contribution can be raised up to 80-85% if the intervention generates an improvement of two or more classes. An important aspect of this regulation is that the credit from the tax deductions can be directly transferred from the building owner to the construction company who execute the work. More recently, as part of the financial stimulus in response to the Covid-19 crisis, the Italian Government is trying to boost the construction sector by increasing the tax relief to 110% of the retrofitting cost (Government of Italy 2020).

Starting from these considerations, this work discusses the retrofitting of traditional Nepali SMM buildings and tries to answer two important questions: (i) what is the Return on Investment (ROI) of retrofitting traditional stone-masonry buildings? (ii) Can standard retrofitting approaches be subdivided in incremental steps to spread the upfront investment over a longer time? Section 2 describes the two retrofitting technologies currently approved by the National Reconstruction Authority (NRA) and describes an incremental subdivision of these interventions. Section 3 discusses the structural vulnerability of the incremental steps and presents the cost-benefit assessment methodology adopted in the study. Lastly, Section 4 includes the discussion of the results in terms of ROI of retrofitting.

2. Retrofitting approaches in Nepal

In response to the 2015 earthquake event, the Government of Nepal, through the National Reconstruction Authority, has reviewed and approved two seismic retrofitting approaches for traditional masonry houses. Under the Government of Nepal housing reconstruction program, homeowners of partially damaged buildings can access a grant of 100k NPR to retrofit their properties (National Reconstruction Authority 2017). These two approaches, namely the Strongback (STB) and the Splint and Bandage (S&B), are described in the following subsections.

2.1.Strongback (STB)

The STB system (Figure 1a), developed by Build Change, is designed using the Nepal Building code NBC105:1994 (Department of Urban Development and Building Construction 1994). The STB retrofit refers to the addition of vertical reinforced concrete (RC) braces, or STBs, at the corners and at regular centres along the internal face of the masonry wall. These STBs are connected to the wall via RC “through-ties”, which aim to facilitate transfer of seismic forces between the wall and the STBs, as well as reducing the susceptibility to delamination of the multi-leaf wall. The RC elements play an important role in tying the walls back to the floors, providing a load path for the out-of-plane wall loads to reach the diaphragms above and below. The installation of STBs to prevent the out-of-plane action of URM walls is an established practice for typical brick masonry buildings in the United States and has been identified as a standard retrofitting technique in FEMA 547 (Federal Emergency Management Agency 2006) and FEMA P-774 (Applied Technology Council 2009). At floor level, a 100mm thick RC 'slab strip' is provided around the perimeter and at two interior cross tie locations. The strips are supported vertically on the floor joists and doweled to the STBs and building walls. The objective of the slab strip is to improve the wall-to-floor connections and to increase the diaphragm action. At eaves level, a 150mm deep RC ring beam is provided, with a width equal to the thickness of the wall. The roof rafters are tied to the ring beam via metal straps embedded in the concrete, and L-bars are provided to connect the STBs to the ring beam. The heavy masonry gable is removed and replaced with a lighter corrugated iron one and the connections within the roof structure are improved. As a final step, the building walls are covered internally and externally in a cement-based plaster. The general implementation procedure for the STB is: 1) site clearance/fixing of scaffolding/removal of existing plaster; 2) repair of cracks /placement of through concrete; 3) construction of ring beam; 4) construction of foundation for strongback; 5) construction of strongback and connection to walls with dowels; 6) construction of slab strips; 7) plastering; 8) roof connection improvement.

The STB approach has not undergone a full-scale shaking-table or pushover test, however, it refers to a number of experimental tests on the effectiveness of the constituent elements: experimental shear-compression tests on SMM piers with and without cement plaster (Build Change 2018) to estimate shear and drift capacity at element level; vertical and diagonal compression tests on SMM samples to investigate the influence of stabilized soil plaster, cement-based plaster and through-ties on material's shear strength and stiffness (Build Change 2016; Build Change 2019); compression tests of stones from the mid-hills of Nepal (Build Change 2015).

2.2.Splint and Bandage (S&B)

The S&B method of retrofitting masonry buildings is designed according to NBC105:1994 (Department of Urban Development and Building Construction 1994) and is based on providing horizontal and vertical strip elements at critical locations of the structure such as corners, wall intersections, openings, floor/roof-to-wall junctions, etc. (Figure 1b). This enhances the seismic performance of masonry walls improving in plane response and reducing localized out-of-plane failures. In Nepal, one of the first introductions of this technique was done in 1999 when, as a pilot of the School Earthquake Safety Program (SESP), the National Society for Earthquake Technology – Nepal (NSET) implemented the retrofitting of Bhuwaneshwory Lower Secondary School at Bhaktapur using this method (Asian Disaster Preparedness Center 2003). The vertical (splint) and horizontal (bandage) elements provided along both the outside and inside surface of the load bearing walls are designed considering both in-plane and out-of-plane behaviour. In case of low strength masonry, Galvanized Iron (GI) wire mesh is additionally provided at other locations of the walls to prevent local failure and spalling of masonry units. Through wires or semi through connectors are provided on the walls at certain intervals in a staggered fashion to tie the inner and outer meshes together in all locations of the wall. Depending on the design and various other factors, either rebars or welded wire mesh can be used as reinforcement encased in a (1:1.5:3) concrete layer of 40mm thickness or plaster. When rebars are used as reinforcing elements, micro concrete (with aggregates less than 10mm in size) is adopted. Rich 1:3 cement plaster is applied when wire meshes are employed as reinforcement. The application of concrete or plaster is solely manual, and hence applied in two layers. For the outer surface of walls, both the welded wire mesh and GI wires are provided with a plaster layer of 30mm thickness, while 20mm of plaster is provided on the interior surface. The GI mesh is comprised of wires which is usually placed further apart than those in the welded wire meshes, according to design. Reinforcing elements of the splints along with the vertical GI wires are tied to the floors and to an anchorage/tie beam at the base of the building. A wider tie beam is provided when rebars are used for the splints. The general process of implementation of retrofitting work using steel wire mesh includes: 1) Removal of existing plaster from walls in the proposed area 2) Raking out mortar joints to 15-25 mm depth, air cleaning and wetting the surface 3) Excavating the soil for tie beam and laying the reinforcement 4) Applying the wire mesh on walls and providing anchor rods or through wires to tie inner and outer wire mesh firmly with the wall 5) Anchoring the wire mesh to the rebar of the tie beam 6) Concreting the tie beam 7) Applying plaster to the wall 8) Curing.

Over the last years, several versions of the S&B method have undergone full scale experimental tests (Shrestha et al. 2012; Bothara et al. 2019) that have validated the good seismic performance of the technique. Additionally, empirical evidence after the 2015 earthquake has shown that almost all buildings (mainly schools) retrofitted with the S&B technique, whether in areas of low or high ground shaking during the event, performed very well (NSET 2015, Wang et al. 2018).

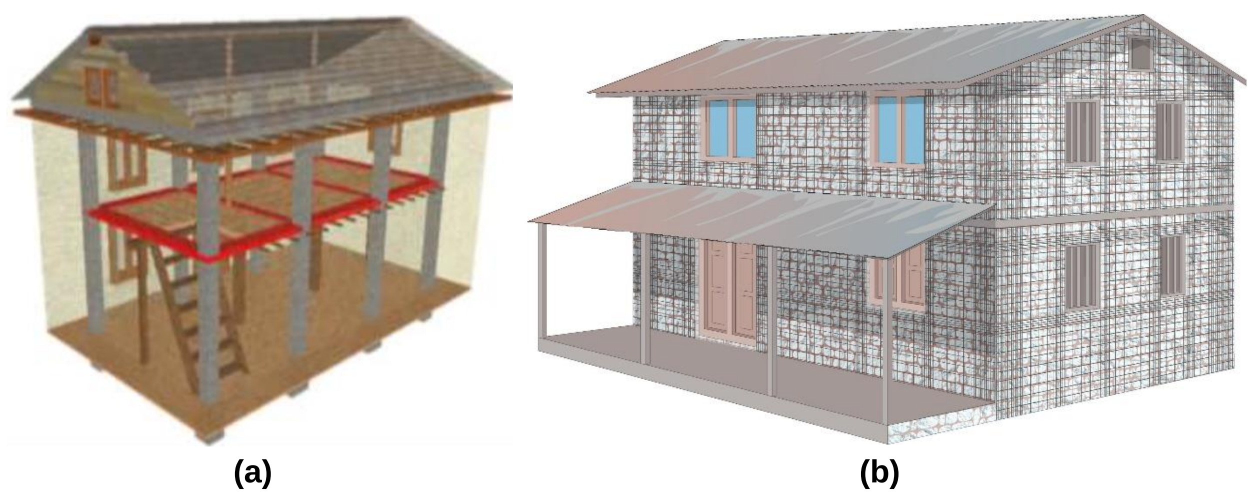

Figure 1 - Retrofitting strategies in Nepal: (a) Strongback (STB), (b) Splint and Bandage (S&B)

2.3.Incremental retrofitting subdivision

To allow partial and incremental interventions, herein the STB and S&B approaches are broken down into a number of discrete retrofitting elements which are then assembled into phases or steps (Table 1). In Phase 1, both techniques include the substitution of the masonry gable with a light weight corrugated galvanized iron (CGI) sheet and the improvement of roof connections. In addition to these two measures, Phase 1 of STB includes the casting of the RC ring beam to the top of the walls (subsequently connected to the vertical frame elements) and the installation of RC through-ties. While Phase 1 of S&B includes the construction of the roof band with welded wire mesh. Phase 2 represents the most demanding part of the incremental retrofitting since it involves the construction of the RC elements (STB) and the realization of the splints and bandages (S&B). From a structural point of view, Phase 2 corresponds to a consistent upgrade of the building's seismic response. Thanks to the new connecting elements, wall-to-wall and wall-to-floor connections are consistently improved and the building can respond in a box-like manner under seismic loads (Giordano et al. 2020). Therefore, Phase 2 represents the turning point from predominant out-of-plane damage to in-plane damage. The last step of the incremental processes consists in the plastering work. For STB it involves the use of cement based plaster while for S&B it also includes wire mesh reinforcement.

Table 1 - Incremental phases of retrofitting for STB and S&B approaches

	STB	**S&B**
Phase 1	- Replace stone gable with a light weight CGI sheet - Improve the connections of roofing members - Cast a ring beam to the top of the walls - Install RC through-ties in the walls	- Replace stone gable with a light weight CGI sheet - Improve the connections of roofing members - Construct a roof band with welded wire mesh
Phase 2	- Install vertical reinforced concrete strongbacks - Install reinforced concrete slab strips at floor levels	- Construct splints and bandages - Improve floor action*
Phase 3	- Apply cement based plaster on the external and internal faces of the walls	- Jacketing with wire mesh - Apply cement based plaster on the external and internal faces of the walls
***** floor-to-wall connections and/or floor diaphragm strengthening depending on solution		

3. Cost-benefit assessment

The cost-benefit analysis is carried out considering a nominal life of the SMM-URM building equal to 30 years (Department of Urban Development and Building Construction 1994). The analysis is performed with reference to an archetype index building characterized by: two stories, average interstory height of 2.1 m, average in plan shape of 4 m × 8 m, average wall thickness of 0.5 m. Retrofitting benefit (B) can be quantified in different ways; however a common measure to estimate mitigation measures is in terms of reduction in future Expected Annual Loss (EAL) before and after the application of the retrofit (e.g., Liel and Deierlein 2013; Giordano et al. 2018). Similarly, the cost (C) can be annualized to quantify the ROI = B/C (e.g., De Risi et al. 2018). The ROI can be directly used as a decision making tool: if ROI is larger than one, the mitigation measure is in fact financially advantageous.

3.1.Vulnerability assessment and benefit quantification

The first step to quantify the benefit of a retrofitting measure consists of calculating the vulnerability curve of the structure before and after the intervention. In this work, vulnerability curves are estimated for the original building and at each retrofitting phase. A building's vulnerability function correlates a representative Intensity Measure (IM) of the earthquake (such as the Peak Ground Acceleration, PGA), with the repair to replacement cost damage ratio. Vulnerability curves can be derived from damage fragility curves through consequence functions (Figure 2) (e.g., Rossetto et al. 2014) where: (i) fragility curves are probability of exceedance functions of damage states (DS), and (ii) consequence functions express the repair to replacement cost ratio of each DS.

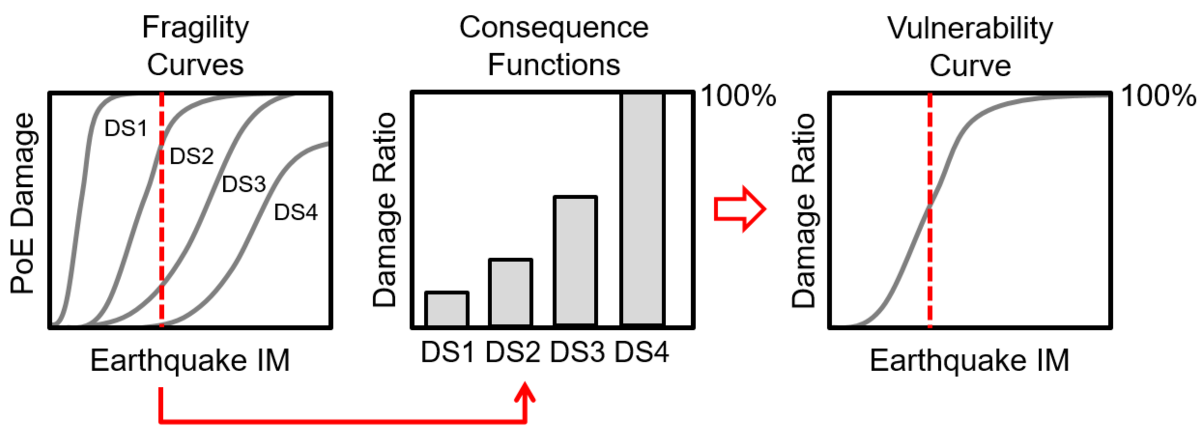

Figure 2 - Derivation of vulnerability curves from damage fragilities and consequence functions (PoE = Probability of Exceedance)

In this work the fragility curves are calculated using the analytical model developed by Giordano et al. (2019) where four damage states are considered: DS1 - slight damage, DS2 - moderate damage, DS3 - severe damage, DS4 - near collapse. This method considers the in-plane and out-of-plane damage potential depending on the characteristics of the building. A fully probabilistic Monte Carlo approach is adopted to derive fragilities where random variation of mechanical parameters, geometry and seismic record are directly taken into account. In absence of specific consequence functions for Nepali SMM buildings, HAZUS relationships are adopted (Federal Emergency Management Agency 2015).

Figure 3 reports the vulnerability results of the two retrofitting approaches (STB and S&B) for each incremental phase. The effect of structural interventions has been directly taken into account by modifying the input parameter of the fragility model according to experimental tests and literature studies (e.g., de Felice 2011; Kadam et al. 2015; Wang et al. 2018).

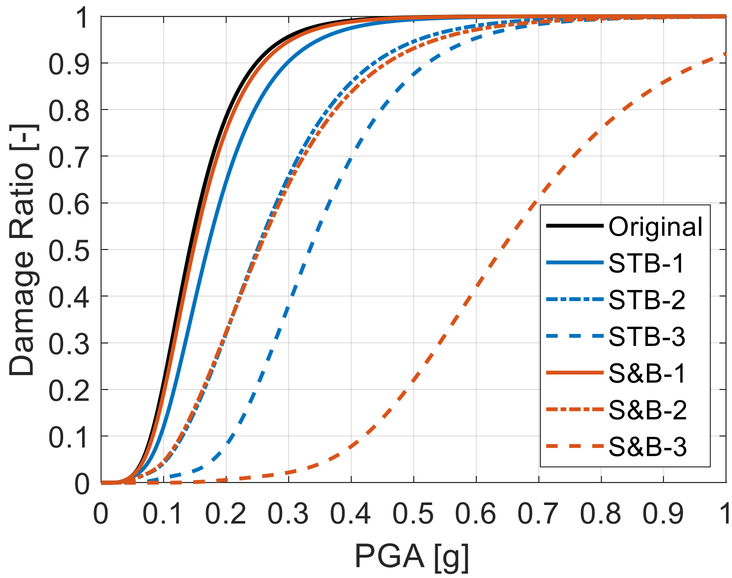

Figure 3 - Vulnerability curves for different retrofitting solutions and incremental phases

The vulnerability results show that:

- Phase 1 of both approaches provides a slight decrease of vulnerability with respect to the original structure since it refers to limited interventions, such as the gable replacement. Phase 1 of STB provides a larger reduction of vulnerability given the presence of RC through-ties.
- Phase 2 generates a consistent increase of seismic capacity for both STB and S&B solutions. As previously mentioned, the building does not respond as a system of loosely connected walls but as a 'box-like' structure. The out-of-plane damage is now limited to the portion of walls between adjacent STB or S&B. Consequently, the in-plane failure mode becomes the critical one.
- The last phase corresponds to the code-compliant retrofitting solution currently approved by the NRA. Even though it is not fully consistent to compare design results with vulnerability results (in the first case the assessment is carried out deterministically rather than probabilistically), it is observed that for both techniques the damage ratio at PGA = 0.3 g is lower than 50%. This ground intensity level corresponds to the PGA that is used to design for life safety for a SMM house with nominal life equal to 30 years. Additionally, 50% damage ratio is generally considered equivalent to the life safety limit state (Federal Emergency Management Agency 2015). Lastly, it is noted that Phase 3 of the S&B approach provides a consistent increase of seismic capacity given the presence of the steel

wire mesh. In fact, the reinforcement acts as additional protection against in-plane and out-of-plane damage.

From the vulnerability curves the benefit of each retrofitting step is estimated through the expected annual loss EAL with the following equation (Porter 2018):

$$EAL = V \int_0^\infty y(s) \frac{-dG(s)}{ds} ds \quad (1)$$

where G(s) represents the hazard, i.e. the mean annual rate of exceedance of PGA as for Stevens et al. (2018), V is the replacement cost of the building, y(s) is the vulnerability curve. The benefit of a given retrofitting phase is calculated as the difference between the EAL before and after mitigation:

$$B = \left(V \int_0^\infty y(s) \frac{-dG(s)}{ds} ds - V_m \int_0^\infty y_m(s) \frac{-dG(s)}{ds} ds\right) \left(\frac{1-e^{-\rho t}}{\rho}\right) \quad (2)$$

where V_m and y_m refer to the retrofitted building, ρ is the real discount rate assumed equal to 7% for Nepal (CIA 2017) and t = 30 years is the planning period. In this study, the replacement cost of the building has been considered constant and equal to 1012.3k NPR.

3.2.Cost quantification

The cost estimation of the index building has been carried out by NSET and Build Change. NSET has gained experience through the years on the S&B technique by retrofitting and providing technical assistance to over 300 buildings, including 56 buildings in the recent Baliyo Ghar Project. Build Change has enhanced its global experience through implementing and providing technical assistance to 332 STB and 18 S&B retrofits in Nepal. Three retrofitting cost estimates are provided in this work: one for the STB approach and two for the S&B approach. It should be noted that fluctuation in construction costs is generally high in Nepal and largely affected by building geometry, local availability of materials, cost of the workmanship and transportation. Table 2 reports the breakdown of the costs with respect to the incremental steps.

Table 2 - Cumulative cost of incremental retrofitting phases

	STB[1,*]	**S&B[2,*]**	**S&B[3,*]**
Phase 1 [kNPR]	162	61	32
Phase 2 [kNPR]	326	279	148
Phase 3 [kNPR] (total cost)	445	517	273

[1] estimate based on the experience gained in retrofitting 332 buildings
[2] estimate based on the experience gained in retrofitting 18 buildings
[3] estimate based on the experience gained in retrofitting 300 buildings
* Note: the estimates provided in this table have not been validated by an independent third-party

Once the initial costs are estimated they are annualized for a consistent comparison with the EAL reduction. The following equation is adopted (De Risi et al. 2018):

$$C = C_m \cdot \frac{\rho}{1-(1+\rho)^{-t}} \tag{3}$$

where C_m is the upfront cost of the retrofitting intervention.

4. Discussion of the results

The last step of the analysis is the estimation of the return on investment ROI = B/C. In Figure 4 the results are reported. The green bars correspond to the total ROI of the retrofitting phases with respect to the original configuration. The light blue bars refer to the relative ROI between consecutive incremental steps. It is noted that the S&B solution reports multiple values of the ROI since two cost estimates are available.

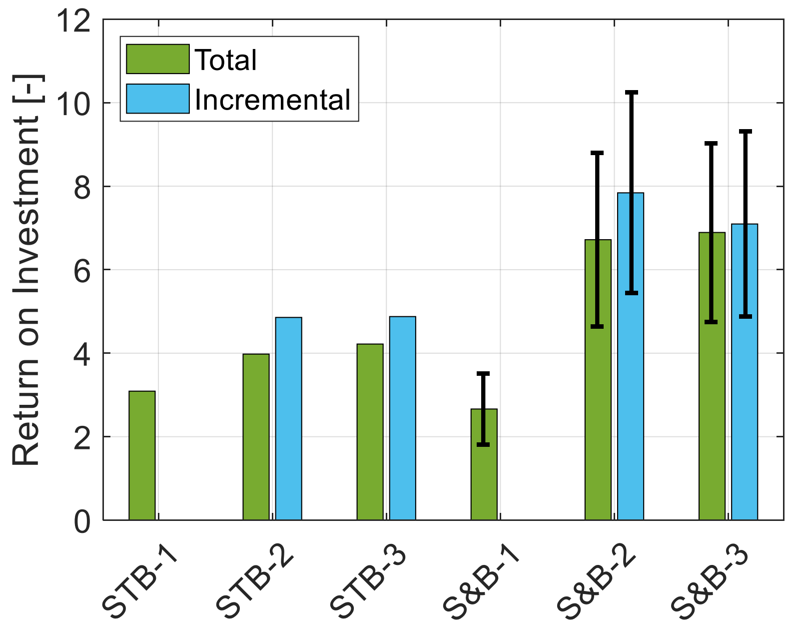

Figure 4 - ROI for different retrofitting solutions and incremental phases

On average, both retrofitting techniques provide a total ROI larger than four i.e. every dollar spent in retrofitting pays back four dollars over the thirty-year lifetime of the building. This also implies that retrofitting investments are paid back in less than seven years. This result largely justifies investments in retrofitting traditional SMM masonry constructions in Nepal. The incremental ROI is always larger than four meaning that the subdivision in phases is well-balanced in terms of costs and benefits. In general, it is observed that the lower bound of ROIs of S&B is roughly equivalent to the values available for STB.

As expected, Phase 1 provides the lowest ROI. This is because some of the interventions cannot be taken into account in the fragility model (e.g. the connections of roofing members).
Variation in retrofitting costs represent an important factor when assessing the ROI as it is observed from the S&B results. Interestingly, large fluctuation in costs do not change the outcome of the analysis and still demonstrates the effectiveness of retrofitting.

5. Conclusions

In Nepal the earthquake risk remains one of the major threats to the safety of the population and the stability of the economy. For this reason, it is imperative to focus resources on mitigation measures. Experiences from other seismic prone-countries show that retrofitting policies have been strongly promoted to improve the overall performance of the building stock when subjected to an earthquake event. A safer building stock decreases the risk of fatalities and generates lower direct or indirect economic losses. Additionally, it allows more knowledge, to incorporate financial resilience mechanisms like catastrophe insurance. Partial and incremental retrofitting is nowadays commonly accepted since it allows more flexible risk management actions. It also guarantees a homogeneous distribution of the interventions over the building stock. In this study, a probabilistic cost-benefit analysis has shown that every dollar in retrofitting pays back more than four times over the lifespan of unreinforced stone masonry buildings in Nepal. This means that Governments, supported by donors, could increase resilience in line with the Sendai goals and receive a higher return on their investment. Another important aspect is that current retrofitting technologies can be split into different intervention phases. Thus, retrofitting works can be carried out gradually when financial resources become available. This result represents an important outcome for policy makers and international organizations interested in financing risk reduction programs in the context of Nepal.

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