# Decision support model for seismic strengthening technology selection of masonry buildings

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# DECISION SUPPORT MODEL FOR SEISMIC STRENGTHENING TECHNOLOGY SELECTION OF MASONRY BUILDINGS

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Original scientific paper
When the decision has been made to seismically strengthen a building, in order to mitigate possible damaging effects of an earthquake, choice of seismic strengthening is entirely left to the expert. The choice is often made without any specific analyses of the need and implementation possibilities, but depends completely on the expert's knowledge and experience. The article presents the development of the innovative approach to strengthening technique selection for existing buildings that incorporates all important elements that influence the strengthening selection process. The presented model is simple, quick, precise, allowing analytically supported decision making. Although the developed model is designed particularly for masonry buildings, decision support model for strengthening technique selection is adaptable to any building type.

**Keywords:** *decision support model; existing buildings; innovative approach; masonry; seismic strengthening technology*

**Metodologija odabira tehnologije seizmičkog ojačanja zidanih zgrada**

Izvorni znanstveni članak
Kada je donesena odluka o potrebi za ojačanjem zgrade u cilju preventivne zaštite od potresa, kao pravilom, odabir ojačanja prepušten je stručnjaku. Odabir ojačanja se najčešće provodi bez konkretnih analiza mogućnosti i potreba za određenim pothvatom, već isključivo prema nahođenju i prošlom iskustvu stručnjaka. U članku se predstavlja proces razvoja inovativnog pristupa izboru tehnologija ojačanja postojećih zgrada, a kojim se uzimaju u obzir svi bitni elementi koji mogu utjecati na izbor ojačanja. Predstavljeni model je jednostavan, brz i precizan, te dozvoljava donošenje odluka na osnovu analitički dokazanih činjenica. Unatoč tomu što je model izrađen isključivo samo za zidane zgrade, model za izradu potpore odlučivanja pri odabiru tehnologije ojačanja je prilagodljiv bilo kojem tipu građevina.

**Ključne riječi:** *inovativan pristup; model za odabir tehnologije; postojeće zgrade; tehnologije seizmičkih ojačanja; ziđe*

## 1 Introduction

To enable a simple, but analytically supported decision on how to seismically strengthen masonry, or other existing buildings, an overview over all elements that could influence this decision should be provided. Normally the choice of strengthening is done based on experts past experiences. Also a part of engineering knowledge plays a part in decision making. Criteria based on which normally a decision is made are by experience proven method of achieving the desired strengthening effect and basic compatibility of the strengthening technique with the building structure. What happens if the experiential knowledge was not really proven to be effective? Since the decision is based on one expert's experience, is the strengthening technology going to be changed if the expert changes during the project execution? Research shows that a decision on the selection of seismic strengthening technology needs to be based on analytically correct and verifiable criteria. But also, the selection process of the strengthening technology needs to take into account all the criteria that could at any point of the project change the perception of the previously made decision.

A number of strengthening selection approaches exist, where EC8 [1, 2] is the least helpful support and FEMA 547 [3], with a set of other FEMA handbooks the most complete support when deciding on how to strengthen an existing building. There are a number of other approaches as NZSEE recommendations [4, 5], or Canadian NRC guidelines [6]. Lately international projects as NIKER [7] and World Housing Encyclopedia [8] have been concentrating to provide a technique selection data set. All those provide a decision support on how to strengthen an existing building, but none of those do it in a simple, non-ambiguous way providing at the same time analytical support for the selection of propper strengthening technology, as will be comented later on.

In this article, a simple, fairly quick, but analytically correct and verifiable methodology for seismic strengthening technology selection for masonry buildings is presented. The use of the strengthening selection methodology leads an expert of the field through the process of technology selection. This way the expert can gain the full insight into all the possible intervention techniques, indications and contraindications when and how to use the strengthening technology, and finally, at the end of the selection process, when the list of possibilities has been shortened, for the remaining suggested intervention technologies costs are assessed. As for each intervention technology its contribution to seismic safety of the building is evaluated, finally the most cost-effective technology can be suggested.

The research on technology selection support was done to aid a holistic seismic risk mitigation model, therefore, the strengthening technology selection model was developed to be non-ambiguous, simple and preventing possible halts in the process of strengthening selection, even in cases when cultural heritage is to be strengthened.

Based on these research goals the next research questions were set: Which decision support elements are essential for proper selection of strengthening technologies? Do existing models provide satisfactory decision support? If not, using a number of existing model elements, can a new decision support model be formed to provide a quick, simple and analytically correct decision support? If yes, how can this decision support change or improve the selection of seismic strengthening techniques? And finally, what is the proper way to select a strengthening technique using the new decision support?

## 2 Research and methods

Research was structured into a number of research parts, according to different research aims:

- **focusing the research**:

Research was focused by selection of specific building generation by buildings characteristics and construction years. These two criteria ensured simplification in research process as, if chosen properly, this way materials, building technologies and problems would be similar. The selection of desired research problem was defined per a combination of expert site reports and literature review. Further on identification of research specifics was conducted by collection and analysis of historical documentation and literature review.

- **building the necessary legislative framework around the selected case**:

Legislative framework defines important and not avoidable design process. For the chosen building typology Croatian legal framework is formed by the Law on construction [9] and Law on protection and preservation of cultural goods [10]. As by these laws a simple intervention selection is not possible, as special intervention approval procedure is required, an additional interview with decision making authority was conducted to gain a better insight into allowed and suggested intervention measures.

- **research on building earthquake resistance characteristics:**

The research on selected buildings typologies' weak points' identification was done by literature review of earthquake reports and other professional literature. This way the research aim for the improvement methods was partially set.

- **criteria identification for decision support model (selection factors):**

Important criteria for technique selection were collected by literature review. There were two types of criteria identification used: criteria that were used in other decision support models and through detailed literature analysis. Detailed literature analysis was used on literature that did not clearly state elements, but was using guidelines on proper usage of a strengthening technique.

- **strengthening technologies – database creation:**

The aim of this part of the research was not to discover new techniques, but collect existing information and experiences on already known strengthening techniques for masonry buildings consisting structural elements and having the expected weaknesses identified in the "research focusing" and "earthquake vulnerability" chapters. Strengthening method list was composed through literature review and case studies from 15 different strengthening and retrofit projects. Literature review and analysis is done in the doctoral thesis [11]. The list was additionally supplemented with experiential strengthening methods collected from a selection of experts of the field. Previously defined important criteria defined also the research topics for each strengthening technology, as important criteria information must be available for each separate intervention method.

To fill the database with necessary data in accordance with identified important criteria, for each intervention technique work breakdown structure was composed. Based on the activities from the work breakdown structure intervention invasiveness, material specifics, quantities and intervention execution specificities were analysed. Intervention costs were collected per expert assessments, past projects' data analysis and standard price calculations. All these prices were statistically analysed resulting in normal expected price and expected price range.

- **decision support simplification and structuring:**

Selection criteria initially formed was composed of a list of criteria, which when answered formed a decision suggestion. The proposed method led to informed decision making, but, due to a too large number of information provided, could cause a misleading suggestion or result with ambiguities. Therefore, a decision support simplification was conducted.

- **selection process modelling:**

The strengthening technology selection process had to be formed in order to ensure all important criteria are given the necessary attention. The selection process modelling was conducted through a formation of work breakdown structure, which was later on reassembled to follow the necessary procedures of construction strengthening design and legally defined framework.

- **model testing and fine tuning:**

Finally, on a generic building example the model was tested. Test revealed a faulty presumption in the model. Therefore, additional model tuning was needed which resulted in additional cost assessment corrections and strengthening contribution testing. The success of the fine tuning was tested on 3 real-life projects.

## 3 Research results

### 3.1 Research focusing

Croatia is an earthquake prone area with earthquake building regulations existing only since 1963. Therefore, buildings built prior to that date can be considered as vulnerable to earthquakes.

According to author Dobrinić [12], the implementation of "solid" construction techniques with brick masonry in the area of Zagreb began during the 1850's. At that time construction principles were taken from Vienna, as during that time the main impact on development was from the influence of Austrian culture, which mostly ended with the end of Austro-Hungarian Empire during the year 1918.

Hereby, the subject of study is defined to be buildings built from 1860's to1920's.

Characteristics of buildings built during this time of interest were: Buildings were shaped mostly with regular building plan [13]. Vertical bearing structure consisted solely of masonry walls built of clay bricks and mortar. Horizontal bearing structure, on the other hand, consisted of masonry vaults above the basement floor, and partially in the upper stories, but mostly, horizontal bearing structures were built of wooden beams and wooden planks [14]. It has to be pointed out, that although this construction typology was considered "solid", it was built with low quality mortar and not interconnected wooden floor constructions according to Kolbitsch [15] and Tomaževič [16]. These findings shaped further research by eliminating strengthening methods not fit for structural characteristics of masonry buildings with wooden or masonry vault floor bearing structures.

### 3.2 Research on legislative framework

Buildings built in time from 1860's to 1920's, in most cases are the buildings that are now a part of old city cores of Croatia. These can, therefore, be considered as built heritage, if any intervention is to be undertaken on these buildings.

According to the Croatian law on heritage protection [10], a special permission for works needs to be issued. This permission has to be issued for each building that is, or can be assumed to be, built heritage. The permission contains suggestions on the materials and building parts that are to be kept as originally constructed.

In order to make the decision making process of the holistic earthquake risk mitigation model continuous, the decision making procedure must not be interrupted by long-lasting permission issuing process as requested per law. To simplify the decision making process an interview with decision making authority was conducted.

The interview results can be summarized as follows:

- generally, it can be assumed that these buildings may not be destructed or disassembled
- in the interest of preservation and safety of inhabitants the interventions can be permitted if historical values are preserved; as elements of historical value can be listed elements like: façade, artistic forms of any kind (floor or wall finishing, reliefs, any visible structural elements)
- in the interest of ensuring allowance on works, interventions should preserve or mimic the technologies used in the past

Of course, these interventions can use modified original building construction technologies as long as the outer (visible) structure remains original or as close to the original as possible.

The reader should be advised that these suggestions are to be used only for the needs of strengthening selection simplification. In case of intervention planning these guidelines can be used only as suggestions, but the final decision needs to be approved by the decision making authority.

### 3.3 Earthquake vulnerability and strengthening

Earthquake vulnerability of buildings comes from their weak points. As was previously mentioned, only since 1963 earthquake design has been introduced into Croatian legislation. Therefore buildings of interest for this research (built from 1860 till 1920) were not designed to cope with strong horizontal motions (earthquake).

Literature suggests that main weak points of these buildings are:

- no proper connection between wooden floors and masonry walls exist [17]. Floor bearing beams are in most cases just positioned on the edge of the wall without any type of wall – floor connection (Fig. 1). These types of connections do not enable the necessary transfer of horizontal loads between floors and walls.
- masonry walls tend to crack due to repeated in-plane shaking, or simply due to low shear bearing capacity [16]
- wooden floors were mainly designed to bear only vertical loads, whereby these can be considered flexible and unable to transfer shear forces [16, 18]
- Gattesco et al. [19] reports of problematic vault behaviour in case of earthquake
- other evidenced weaknesses are mainly building specific: material degradation, foundation and soil problems, etc. [6]

The same failure reasons were evidenced in a number of earthquake reports from all over the world: Celik et al. [18] (Italy), Griffith [20] (Australia), EERI reports [21, 22] (New Zealand), etc.

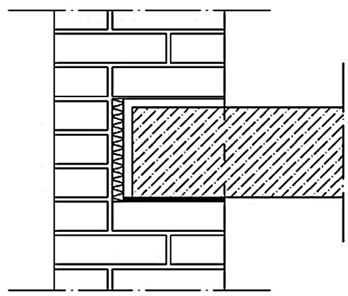

**Figure 1** Typical wall – floor connection (built 1860's÷1920's) [14]. Floor bearing beams are just positioned on the edge of the wall without any proper bonding elements to connect floors and walls

### 3.4 Criteria for strengthening selection

Within the literature review, numerous criteria can be found, based on which the authors suggest strengthening techniques to be selected.

Tomaževič [16] suggests the selection of strengthening according to the type of building structure and its effects on the existing structure. The effects that are taken into account are the problem that can be solved by the strengthening intervention, possible negative mechanical effects or the possible ineffectiveness of the intervention. Similar approach can be evidenced in Canadian guidelines [6], European Norms [1] and according to Kolbitsch [15]. According to authors Tomaževič [16] and Kolbitsch [15], additionally the historical value of the building plays an important role in intervention selection.

The importance of intervention costs cannot be left out. Canadian guidelines [6] present a number of intervention technologies which are supposed to be cost-effective for all existing buildings, though authors of Canadian guidelines do not place a special accent on usability of specific techniques on historic buildings. Further on, Canadian PWGSC has oriented its research towards identification of existing and development of new cost effective intervention methods [23]. Also other authors have shown their interests in cost-effectiveness of seismic strengthening of buildings as Bostenaru et al. [24], SIA [25], or FEMA [26].

Although not often mentioned when talking about seismic strengthening, material interactions are also to be taken into account, according to NIKER research program results [27]. The other criteria are also the behaviour compatibility of building specificities and the intervention according to Bothara et al. [28] and Corradi et al. [29], NRCC [6] and many others.

Finally, a set of decision support criteria have been identified and selected as important:

- problem resolved by the intervention – which building weaknesses can be resolved by the specific strengthening technique
- technology contribution to resistance increase
- what elements are needed for the intervention to be effective, if any – what additional improvements need to be done for the intervention to be effective; e.g. stiffening the wooden floors may have reduced strengthening effect if the floor is not anchored to the walls
- when should the technique not be used – what are contraindications for a certain strengthening
- invasiveness of the technique – how much of the original structure should be preserved if a certain technique is used, e.g. introduction of vertical confinement is extremely invasive since each corner or wall end must be partially dismantled
- applicability of the technique for built heritage – if materials and techniques could have been used in the history
- technique material and behaviour compatibility
- cost.

### 3.5 Strengthening technologies

While reviewing and identifying important criteria for strengthening selection a list of possible strengthening technologies was collected. The list was additionally supplemented by expert experiential intervention techniques. By combining the collected strengthening technologies list and important criteria list a database framework was created. Within the database for each strengthening technology an adequate criteria description was filled. Strengthening technologies database was filled with the information on each important criterion and each strengthening technology. Since the main aim of the database creation was not discovery of new strengthening techniques, but collecting existing techniques together with all the important information on each separate technology the main contribution to body of knowledge was discovered in three areas:

- technology contribution to resistance increase
- technology processes research
- and technique execution costs.

#### 3.5.1 Technology contribution to resistance increase

Contribution study was divided into two important segments: resistance contribution of vertical bearing structure and resistance contribution of horizontal bearing structure of the building.

Regarding vertical bearing system, each strengthening contributes to seismic resistance of vertical bearing structure. These contributions vary on the original bearing structure and the strengthening technology applied, and therefore these cannot be generalized. For each strengthening of the vertical bearing structure formulae for resistance calculation of the strengthening or strengthening contribution are provided, if such exist.

The strengthening of the horizontal bearing structure, on the other hand, can be generalized. Strengthening techniques of the horizontal bearing structure can be divided into two groups: techniques that ensure in-plane rigidity of the horizontal bearing structure (slab) and those that do not. The strengthenings that do not contribute to in-plane rigidity can automatically be excluded from the decision support model. Those strengthening techniques that can contribute to the in-plane rigidity of the slab are left in the model and can be taken into account without any special need to recheck their contribution, as long as limit states of their usefulness are known. These extreme simplifications in the model were made on the basis of the EuroCode calculation presumptions.

The EC6 [30] and EC8 [2] when attempting to assess the resistance capability of an existing building presume floors (slabs) to have enough in-plane stiffness to ensure equal peak horizontal movement of walls. These are presumed either on each floor, or at least at the top of the building. These presumptions set by EC can be only valid if slab constructions are rigid enough to ensure almost equal shear transference to each wall connected.

As historical buildings built in the era from 1860's – 1920's were mainly built with wooden floors which could not ensure in-plane stiffness, ensuring in-plane shear stiffness of floors should be the first element that has to be considered when strengthening these old buildings.

#### 3.5.2 Technology processes researches

Analysis of each strengthening technique on the basis of execution processes and interaction with the existing building was requested in order to identify indicators and contraindications for strengthening technique usage. Therefore for each strengthening a WBS was made.

Going through the WBS for each strengthening and scanning for indicators that were identified through literature analysis led to contraindication identification, which is pointed out in the model. Usage contraindications were identified through indications to use a strengthening on one building type based on strengthening intervention and original structure mechanical compatibility [29, 31], or new and old material chemical compatibility [27], or strengthening technique and its wanted and unwanted effects on the strengthened building [3], or even research results from the legislative chapter of this paper.

Research resulted in five simple questions used for contraindication identification and data collection:

- Does the need for partial or complete removal of building finishing works exist? If yes, which ones?
- Is the strengthening technology compatible to building materials? – mechanical, chemical, executional compatibility
- Are there any special needs for the strengthening technique?

- Are the materials compatible with historical construction techniques? If not, is the intervention removable?
- What are the basic material needs for strengthening execution?

### 3.5.3 Technique execution costs and feasibility

The research aim of this part of the research was to: possibly enable identification of execution feasibility and provide a quick insight into strengthening costs in a quick and precise manner.

For testing of shortened cost comparison procedures strengthening costs including all necessary works for 3 different example buildings were assessed. For each building costs were assessed for 5 strengthening techniques for floor structures and 5 strengthening techniques for walls giving in total 25 strengthening combinations with prices for each building. Hereafter, those 75 combinations were ranked according to prices starting from low to high priced interventions. The research was conducted in several attempts to setup the simple as possible, but accurate cost comparison basis.

1st cost comparison attempt:

At first the 1st research question: Are strengthening costs comparable on measure of unit, based only on strengthening material and implementation costs, not taking into account preparation or repair costs?

2nd research question: Is it possible to assess the intervention feasibility taking into account the same presumption as in the 1st research question?

This presumption should help the decision based on costs, avoiding complicated assumptions or time consuming intervention calculations. Here for strengthening costs were assessed in a unit of measure, e.g. 1 m length, including all necessary materials and works needed.

When comparing the rankings of the intervention costs in terms of unit costs to complete intervention costs including all necessary works, the cost rankings of the intervention costs by unit costs gave completely wrong results. Herby building strengthening cost comparison research resulted disappointingly: cost comparison amongst strengthening options by comparing the unit costs and not taking into account preparation or repair costs, gives completely wrong insight into price rankings, whereby no connection to true intervention costs could be made.

This analysis result, although negative, is understandable. Intervention unit costs do not take into account a number of prerequisites which simply cannot be ignored to assess the intervention cost rankings, where by these unit price comparisons cannot be taken as relevant. Herby, the 2nd research question could not be answered positively.

2nd cost comparison attempt:

Due to previous research results, 1stresearch question was altered: Is it possible to compare strengthening costs based on strengthening costs for the whole building, but not including preparation work costs, or repair costs?

Again, accuracy of cost regularity was controlled through complete intervention cost assessments, as was explained before.

This time, comparison of cost rankings between cost assessments not taking into account preparation and repair works and complete intervention costs showed some regularity, whereby partially, still major discrepancies were discovered.

Yet, for those intervention costs showing regularity in rankings compared to full intervention costs, possibility to assess feasibility was researched. To assess the feasibility of a strengthening project, intervention costs were compared to construction costs of equally sized, but new building, where costs to construct a new building were calculated according to the standardized price calculations [32]. The feasibility limit was set preliminarily at 30 % of construction costs. This feasibility limit, as used in Indian Standards [33], was chosen as it was the simplest "model" used in any standard.

After a set of tests on 3 previously assessed buildings on which intervention and construction costs were assessed, test showed an interesting result: no matter how the building was to be strengthened, only the constructive strengthening costs would never accumulate over 10 – 15 % (mainly around 100 €/m$^2$, but up to 150 €/m$^2$) of construction costs for a new building of a similar size.

By comparing the research results to complete intervention costs, the altered 1st research question was answered: No, not even if strengthening costs for the whole building are compared (not including preparation and repair works), strengthening intervention costs comparison cannot suggest the correct price relations. Hereby, even the intervention feasibility cannot be assessed if preparation and repair costs are ignored!

To correctly asses strengthening costs, assign intervention cost rankings and to be able to assess the intervention feasibility it is necessary to include all works: preparation, constructive strengthening and repair works after all works are done.

Although strengthening costs are an interesting feature and an important aspect of strengthening works, based on the presented research results, it was concluded:

- intervention feasibility or the right price ratios cannot be assumed based only on intervention works costs. This is due to the fact that intervention works costs do not increase proportionally with complete intervention costs as when preparation and repair costs are included.
- in order to be able to assess intervention costs and intervention feasibility it is necessary to include all works and cost estimations cannot be shortened effectively
- strengthening works costs are extremely low comparing complete intervention costs (never above 10÷15 % of construction costs for a new buildings) and therefore all strengthening works should be done at the same time as other retrofitting works (e.g. energy efficiency works, or general renovations works…)

## 3.6 Selection model information grouping

The strengthening selection support model is intended to be simple and accurate, therefore complicated data analysis cannot be acceptable. Before a model was created, it was proven that none of the studied models can provide the needed criteria:

- to provide a simple, non-ambiguous, but analytically supported decision support when selecting a strengthening technique for the desired building type.

Existing strengthening selection decision support models were studied, and research results are shortly presented in table 1 and further explained as follows:

- EC8 [2] provides a resistance assessment which is to be done only by analysis with finite element models, whereby not even the contribution of the strengthening can be known without these calculations. On the other hand strengthening techniques are just listed, without any explanations or helping descriptions.
- NZSEE recommendations [4, 5] provide a short overview of applicable strengthening techniques with design comments, but neither strengthening contribution, nor costs are commented
- NRC guidelines [6] provide a similar information pool as NZSEE recommendations commenting each strengthening more in detail providing strengthening implementation schematics as well
- NIKER Catalogue [7] provides a simple and intuitive intervention technique list, but in order to select and analyze the contribution of a specific strengthening technique the user needs to spend time analyzing scattered information that is partially provided. And even then, it is unclear how NIKER Catalogue is supposed to help the intervention planning engineer.
- FEMA 547 [3] is a type of a strengthening techniques catalogue. The catalogue is intuitively simple to use and a list of intervention techniques is suggested for each building weakness. Each strengthening is described in detail, but the final strengthening selection is left to the engineer's professional decision. Costs are also not considered.

The strengthening selection support model is intended to be simple and accurate, therefore complicated data analysis cannot be acceptable. Therefore, FEMA's (FEMA 547 [3] handbook) intuitiveness in strengthening selection and tabular presentation was chosen, meaning that for each building weakness a list of applicable strengthening techniques is suggested. NZSEE's (NZSEE recommendations [4, 5]) important information presentation in three groups was selected, with the intention to keep the provided information as short and as important as possible.

For the newly developed model tabular presentation form was used to keep a simplicity and uniformity of information to be transferred to the reader. Also the provided information was kept down to the basics, but still keeping necessary information available. As the aim was to create a simple to use form, where no information was to be lost, a four column table (datasheet) form was chosen (Tab. 2):

- Technology – for each typical building weakness in this column this is the shortest possible description of the technology to be described in the row
- Impact – contains important information on next important selection criteria: problem resolved; technology contribution to resistance (calculation provided if needed); necessary elements for the effectiveness of the intervention
- Considerations – contains all the important indications and contraindications of the technique concentrating on simplicity and accuracy of the information
- Costs – result of price assessment analysis containing prices in unit values.

**Table 1** Existing strengthening decision support models comparison [11]

| Model | Analysis | Strengthening list | Strengthening description | Strengthening contribution | Costs | Decision support |
|---|---|---|---|---|---|---|
| EC8 | partially provided | provided | N/A | N/A | N/A | N/A |
| FEMA 547 | N/A | provided | detailed + schematics | provided | N/A | selection simplified |
| NZSEE | N/A | provided | simplified | provided | N/A | |
| NRC | N/A | provided | detailed + schematics | provided | N/A | |
| NIKER | N/A | provided | partial | N/A | N/A | |

**Table 2** Strengthening technique selection decision support example [11]
(this table is just a sample of a complete decision support for strengthening selection)

| Technology | Impat | Considerations | Price |
|---|---|---|---|
| **Floor strengthening**<br>Double wooden plank diagonal decking of floors | - shear rigidity of floors (no calculations needed)<br>- provided the floors are anchored into walls out-of plane falling-out of walls can be prevented<br>- increase of bearing capacty of floor structures and reduction of floor vibrations | - according to technology execution and materials used technology is considered to be acceptable for built heritage buildings<br>- if not anchored into walls, floor strengthening can be concidered not effective | area<br>16,00 EUR/m²<br>longitudinal<br>14,00 EUR/m'<br>transversal<br>13,00 EUR/m' |
| **Wall strengthening**<br>Reinforcing walls by introduction of reinforcement into vertical / horizontal slots | - increased ductility of the wall<br>- increase in flexural and shear resistance of the wall<br>- calculation considerations<br>$R_{\text{sd, rein. wall}} = R_{\text{sd, mason. wall}} + R_{\text{sd, reinforcement}}$ | - strengthening effective after crack formation<br>- reinforcement continuity and anchoring are important<br>- technology is partially acceptable for built heritage buildings (if execution is possible without disrupting protected wall finishing) | area<br>25,00 EUR/m² |

### 3.7 Selection process modelling

Previously it was concluded that cost estimation does not give proper results, unless all intervention costs are included.

To correct these faults, and yet to shorten the cost estimation process a generic bill of quantities with a collection of all possible site and building preparation and repair works was created. For this purpose, 15 bills of quantities from practice were used. For each collected work from the generic bill of quantities database, a statistical minimum of 3 prices was collected. These prices were used to assess average expected work costs for each generic work from the generic bill of quantities.

Now, once again, the initial model (Fig. 2) was tested on a generic, for model testing purposes created building. Now, with all costs included, the created model gave expected results.

To define the strengthening technique selection process, the process had to be broken into work processes. These were acquired through experience in design process and through regulative framework requirements. Besides this established framework the selection of strengthening must include the newly defined processes of strengthening technique selection (Tab. 2). Hereby, for the strengthening technique selection process the next processes were defined:

- building typology identification
- building screening (on-site and building documentation)
- heritage protection status identification.

These three processes define the introductory document creation and data collection process. In this step, basic building data are collected such as:

- what is the building typology?
- what are the building characteristics which further on define the selection of the possible strengthening techniques
- is the building protected heritage, and if yes, what level of protection.

These three simple questions shorten the list of possible interventions from the strengthening technique decision support list (Tab. 2). This creation of the introductory data collection enables the selection making engineer (the user) to simply identify buildings' weak points and create the "list of buildings' weak points". This process is the next existing element of the model:

- weak points identification

By knowing the building typology and all existing limits of the project (e.g. cultural heritage, accessibility of the building, etc.) the user can simply eliminate not usable strengthening techniques. For each remaining possible strengthening technique intervention cost should be evaluated. This creates the next step of the model consisting of two dependant processes:

- technology selection
- intervention cost evaluation.

This strengthening selection process, as is created, guides the user to select only those techniques that are suggestible for the specific building type and the identified weak point of the building. The repeated cost evaluation process ensures that all possible strengthening combinations are assessed.

Finally, suggestions of a strengthening can be made on a simple strengthening cost ranking creating:

- decision suggestion.

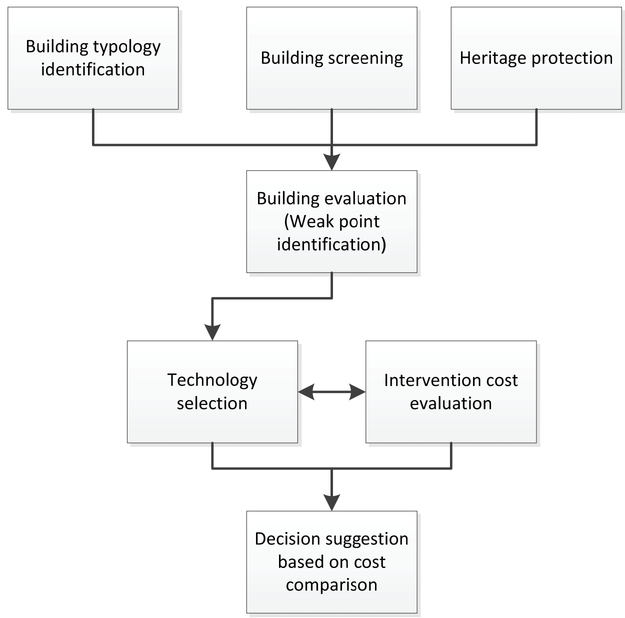


**Figure 2** Strengthening selection process – 1st suggestion

### 3.8 Selection process testing and fine tuning

The model presented in Fig. 2 presents the simplified strengthening selection process and is acceptable if one building is assessed. If a number of buildings are assessed, however, the previous model showed a weakness.

The testing showed that occasionally, although all selected technologies are applicable for the selected building type and the defined border conditions, if the selection process is conducted correctly, multiple choices are available with the same price.

Due to the new insights into model flaws, after further analysis, these conclusions were drawn:

- Model that compares only costs leaves a possibility for the decision making engineer to choose based on experience, which, if possible, should preferably be avoided
- Also, selection model formed this way could not lead to an analytically supported decision making, but a cost based decision making.

In order to be able to make a decision based not only on cost, another costs independent variable had to be introduced. Idea came from the BWG guidelines [25] for seismic evaluation of existing buildings according to SIA 2018. According to these guidelines intervention was to be proven on the comparison of intervention value to value of fatalities decrease due to the intervention. To accommodate the idea in this model "resistance assessment" activity was introduced at two strategic places (Fig. 3).

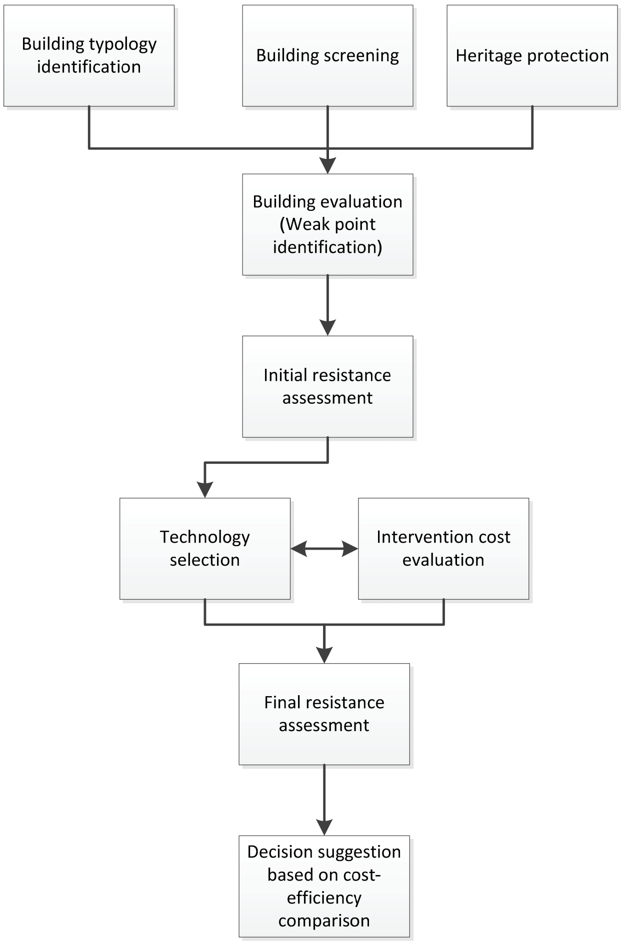


**Figure 3** Strengthening selection process – final process definition

If resistance assessment is executed at the beginning of the selection process, and once again at the end of the selection process, a simple comparison is needed to get a new value: seismic resistance increase due to strengthening intervention.

Now cost to resistance increase ratio gives a new comparison value: cost-efficiency.

By the introduction of cost-efficiency and resistance values the user has the possibility to choose based on several combinations of values: cost, strengthening increase and cost -efficiency.

This way the end user, or the decision maker can easily select among different strengthening technologies or strengthening combinations based on his own preferences keeping in mind that all of the provided results give a satisfactory result regarding seismic resistance of the building. If the selection process is done by the expert, the final decision can now be made by the non-expert (e.g. investor) without a possibility to make a wrong choice.

Finally, to conclude the research, the model was tested on three real life buildings and assessment flow, result correctness and time needed were monitored. The model test went without any interruptions, as all the needed data was collected prior to any calculations were made. Analysis results gave expected results which were in accordance with results compared to models made with finite element models with acceptable discrepancies. And finally, after all the initial data is collected, the analysis using the model can take from 1 to 3 hours depending on the building and the user experience.

## 4 Conclusion

A number of strengthening selection approaches exist. All those provide a decision support on how to strengthen an existing building, but none of those do it in a simple, non-ambiguous way providing at the same time analytical support for the selection of propper strengthening technologies. This leaves the expert deciding on his own how to strengthen one or the other building and almost as a rule coosing a strengthening technique he most often uses.

In this article, a simple, fairly quick, but analytically correct and verifiable methodology for seismic strengthening technology selection for masonry buildings is presented. The use of the strengthening selection methodology leads the expert (or the user) through the process of strengthening selection. This way the expert can gain full insight into all possible intervention techniques, indications and contraindications about when and how to use the strengthening technology. Finally, the user is presented with a list of usable strengthening combinations, all of which are usable and can be chosen based on a combination of three factors: cost, strengthening increase and cost -efficiency.

At the beginning of the research the following research questions were set:

1. Which decision support elements are essential for proper selection of strengthening technologies?
2. Do the existing models provide satisfactory decision support?
3. If not, using a number of existing model elements, can a new decision support model be formed to provide a quick, simple and analytically correct decision support?
4. If yes, how can this decision support change or improve the selection of seismic strengthening techniques?

Based on the research results all of these questions were answered:

1. the following elements are essential for the proper problem insight when selecting strengthening technologies: problem resolved by the intervention; technology contribution to resistance increase; what elements are needed for the intervention to be effective; when shouldn't the technique be used; invasiveness of the technique; applicability of the technique for built heritage; technique material and behaviour compatibility; cost
2. existing models did not provide satisfactory decision support which was simple, correct and analytically supported
3. since existing models did not provide the desired simplicity including all the needed important criteria for decision support a new decision support model was developed. The new model is fairly quick, simple and analytically correct

4. the proposed decision support model, provided it is modified to fit desired typology of existing buildings, can improve selection of strengthening techniques by presenting the user with all the important information in one place, and by its formed three decision support elements it guides the user towards selecting the most desired one based on his defined criteria of desirability; none of the proposed strengthening combinations is wrong, just more or less desirable in given conditions, as the unusable ones are disposed at the start of the process.

Finally, it can be concluded, the proposed model, given it is accommodated for the use on desired buildings, can simplify and shorten the strengthening selection process. The process is created in a way which enables the expert to identify all important border conditions and eliminate unusable strengthening techniques at the start of the process and concentrate just on the selection of the more appropriate ones. Due to variables as cost and resistance increases which are integrated in process elements, these can also be used as suggestion variables in different combinations.

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