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Review of Seismic Retrofitting Strategies for Residential Buildings in an International Context

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Abstract

After increasingly strong earthquakes in the Groningen area in the north of the Netherlands, which are induced by gas extraction, the Dutch government decided to cut output from the gas field as well as upgrade existing houses in this region. Due to the fact, that it is expected, that the frequency as well as magnitude of these earthquakes will rise, the development of structural upgrading strategies plays a major role in this context and a review of possible measurements from other countries has been carried out and will be described within this paper.

The study includes a review of various building codes and general information about seismic resistant buildings in “earthquake-experienced” regions, namely California, Italy and New Zealand. Further on different structural materials, building techniques and seismic retrofitting methods, which are used for residential buildings, will be considered.

Most of the affected houses in the region in and around Groningen are masonry structures, which are vulnerable to seismic loading. This requires a thorough understanding of the structural behavior and performance in order to develop appropriate strengthening and upgrading strategies for them. Based on the experience from other countries various design proposals will be suggested to improve the durability of the existing housing stock in the Groningen area.

Keywords: seismic retrofitting, seismic evaluation, upgrading strategy, seismic vulnerability, international codes, URM buildings.

Introduction

The production of gas in the Netherlands lasts for more than fifty years, which is a result of the extraction from different gas reservoirs spread around the Groningen area.

Seismic statistic surveys show that the path of the future seismic events will probably be in constant increase. Despite, earthquakes were already present in the past, only from 2012 they became a threat for the house
Building stock in Groningen. Indeed, in August of 2012 a magnitude 3.6 earthquake with epicenter in Huizinge caused damages to buildings situated in the Groningen area. After this last event the Nederlandse Aardolie Maatschappij BV (NAM), which is a joint venture between Royal Dutch Shell and ExxonMobil, decided to begin a study of the seismic scenario in order to take appropriate action.

NAM nominated the firm of consulting engineers ARUP for the collection and elaboration of the data about the Groningen seismic situation. ARUP carried out analysis about the seismic risk and structural upgrading strategy, which has represented important clues for the exposition of this paper. The aim of this research project is the elaboration of different retrofitting guidelines provided by international codes in relation to the existing upgrading techniques. Based on the Groningen case, a list of interventions related to a strategy conception will be presented. The typology of retrofitting measures will be established by the scanning of the building to identify its weak aspects. Solutions for possible weakness are ordered on the basis of the complexity of the retrofitting intervention.

1. Typology of Groningen building stock

The study conducted by ARUP[1] furnishes an idea about the typology of house buildings in the Groningen area. In the area above the gas field, the most used construction material results to be the unreinforced masonry, which represents the majority (77%), respect to reinforced concrete, timber and steel. Furthermore, vulnerability tests on the Groningen house building stock have been performed. ARUP, by means of empirical equations selected from literature, carried out an estimation of likely damages to the building stock in case of earthquake with magnitude greater than past events. The estimation tests, based on statistically possible seismic events, pointed out the predisposition of the unreinforced masonry structures to seismic damage. In the scenario of a magnitude 5 earthquake located in Huizinge, tests predicted a damage of the 12% of the unreinforced masonry dwellings in the area. By means of a deeper elaboration of the data resulted by the estimation tests, it is possible to define two groups of URM house building typologies in relation to their seismic vulnerability. The vulnerability of the building sub-typologies is characterized by factors as: wall openness, wall type and building mass. Independent freestanding houses such as detached houses and villa houses show good out-of-plane stability given by the perimeter walls. Indeed, the common regularity both in plan and in elevation of these typologies makes them less vulnerable than other classes. The weak aspects of these structures are represented by the large amount of openings on their facades, which leads to a longer natural period due to the higher flexibility respect to other URM structures.

The more vulnerable house group comprises terraced houses and semi-detached houses. The original design process for these building typologies considers a collaboration between the several connected dwellings, especially for lateral loads acting in the direction parallel to the front and rear facades. Designed to withstand (as lateral force) the wind load only, they present small shear walls in the direction of the longest sides. Therefore, the resistance of shear walls in this direction might be too small to withstand seismic loads, even taking into account the collaboration between consecutive structures.

The more vulnerable house typology has been adopted as reference for the developing of the seismic retrofitting strategy.

2. Weak aspects target of retrofitting

The seismic deficiencies that characterize the URM house building can be described by aspects which make these dwelling prone to structural and non-structural element damages in case of seismic events.

2.1 Overall strength

Since every wall is characterized by a weak direction and a strong direction in lateral bearing capacity, the global strength of a masonry building is directly dependent to the in-plane shear capacity and out-of-plane bending capacity of the structural walls. The ideal performance of a URM structure is the collaboration of load-bearing walls which if adequately tied together act as a box against lateral loads.

2.2 Overall stiffness

URM bearing walls are generally characterized by high rigidity. Therefore the fundamental period of vibration results to be quite low respect to other types of buildings. Given the high stiffness of the URM structure the
horizontal seismic forces cause small displacements compared with flexible structures. URM buildings, though, present highly punctured facade with relatively narrow piers between openings, which can confer flexibility to the building. The presence of flexible façade in addition with lacking strength can increase the displacement and thus the building damages in case of seismic event.

2.3 Mortar joints
Poor mortar joints can represent an issue for the seismic performance of a masonry building. The joint composed by poor mortar materials or just old, causes disintegration of masonry wall units and loss of supports for horizontal element as floors and roof. If the anchorage between mortar and masonry elements does not fulfill the design requirements it defines the strength of the masonry wall, resulting in an unfavorable behavior during a dynamic load as a seismic event.

2.4 Irregularities in plan and in elevation
Load bearing walls of masonry building must follow a regular geometry in plan and in elevation. Rectangular or square plan shapes with load bearing elements arranged in plan respect to the two main axes are preferred for their seismic performance. Irregularities in plan can cause torsional moment due to the ground motion, and therefore concentration of stress occurs in correspondence of the connection.

2.5 Wall-diaphragm connection
One of the most important issue for URM buildings is the connection between floor and roof diaphragms and walls. The horizontals forces, triggered by the seismic motion on the diaphragm level can cause a concentration of load in absence of an adequate bond between floor and walls. Connections may also be used to increase the out-of-plane bending capacity for unrestrained walls. Often URM buildings show weak connections between elements due to weathering and corrosion which have reduced material strength.

2.6 Deterioration of walls
Due to deterioration, URM walls can be weakened. Although their lateral load capacity is still adequate to resist loads which they were designed originally, this may not be the case of seismic loads. Walls can be inadequate slender and susceptible to out-of-plane deformation and damage. Cavity walls represent an issue in the case steel ties connection between them are weakened or missing.

2.7 Diaphragm deficiencies
Diaphragms are essential for ensuring the transfer of lateral loads to vertical elements and for contributing to tie the building together. Timber floors could lack both strength and stiffness, which leads to an excessive flexibility of the diaphragm and therefore to an inadequate distribution of the loads. When large displacements of these diaphragms are possible, wall damages might occur.

2.8 Foundation deficiencies
Foundations are not considered to be one of the most critical aspect of the seismic behavior for URM buildings. Anyway, it has been proved that buildings supported by shallow foundations suffer more than those with adequate deep foundations. Foundation could be susceptible to soil spreading and landslides having a detrimental effect on the URM structure. Dogangun et al. [2]

3. Seismic retrofitting guidelines
Seismic codes aim to provide standards and published guidelines ensuring that in case of a seismic event, human are protected, damages are limited and relevance buildings remain operational. Indications on the codes are given for both new buildings and retrofitting designs in order to control the seismic risk.

3.1 Europe
In the European seismic zones the design of new buildings and the upgrading techniques for existing buildings are regulated by Eurocode 8[3] principally, with the addition of Eurocode 0 till 7 and 9. Eurocode 8 provides a reduced regulation for low levels of PGA (peak ground accelerations), and in the case of very low PGA levels, it does not require any application of these guidelines.

When the URM building can be classified by parameters as “simple masonry building” only simple criteria need to be satisfied. The design criteria for simple masonry buildings regard building aspects such as plan geometry, wall configuration, minimal dimension and details.
3.2 Italy
The Italian regulation for the design of new structures and retrofitting of the existing buildings is described in the NTC’08[4] (Norme Tecniche per le Costruzioni) with the addition of CIRC’09 [5](Istruzione per l’applicazione delle NTC’08). The design of an URM building in seismic areas needs to respect guidelines given for the structural elements requirements. In addition to the regularity in plan and in elevation, the structure should satisfy conditions for diaphragm stiffness, diaphragm connection, wall dimensions and max height, respect to risk class zone. NTC’08, as well as Eurocode, considers differently the case of “simple building”. In the case of simple building no verifications are needed in the building design, but after the retrofitting procedure others conditions must be satisfied.

3.3 U.S.A.
In 2014 the American Society of Civil Engineers released the ASCE 41-13[6] named Seismic Evaluation and Retrofit of Existing Buildings. ASCE 41-13 is a combination of two previous American standard guides, so called Seismic Evaluation of Existing Buildings (ASCE 31-03) and Seismic Rehabilitation of Existing Buildings (ASCE 41-06). The new ASCE 41-13 preserves the three tiers approach given by the ASCE 31-03, while the technical provisions have been taken from the 41-06 as the principles for analytical procedures. ASCE 41-13 provides evaluation guidance for component capacity specifically for URM buildings and allows different ductility factors in relation to different failure modes. The first Tier consists in a screening of deficiencies to resist seismic action for an evaluation only. Tier 2 is the following step, which is intended for both evaluation and retrofit of the building. It leads the user to go over the Tier 1 deficiencies with an appropriate upgrading design. The last Tier, the third, is named Systematic Evaluation. It gives the possibility to choose the analysis method between Linear Static, Linear Dynamic, Nonlinear Static and Nonlinear Dynamic.

3.4 New Zealand
The New Zealand Society for Earthquake Engineering (NZSEE [7]) published in 2006 a document so called “The Assessment and Improvement of the structural Performance of Buildings in Earthquakes” focused in the existing URM buildings guidance assessment. It also refers to structural upgrading methodologies without providing any design procedure for retrofitting. Two stages of evaluation are proposed in the document for the seismic assessment.

The first, the initial evaluation procedure, is a coarse screening involving reasonably resources, which aims to the identification of all those buildings that could be potentially earthquake prone. This step is supposed to be carried out by experienced earthquake engineers on the behalf of territorial local authorities and building owners. The second stage is a detailed evaluation procedure for the assessment of the ULS level of existing buildings reached during earthquakes. It provides information, guidance and formulas in order to provide assistance in the evaluation of strength and ductility of structural components, elements and systems.

4. Improvement of seismic building performance
Based on the historical seismic events experience, and on the analysis of the buildings behavior during the ground motions, some strategies aimed to improve the building can be listed. In order to minimize the weaknesses of general URM buildings and improve their structural performance different approaches may be joined.

- Reduction of element mass
The seismic force acting on a free standing element is proportioned to it mass. This is also the case of non-structural elements such as chimneys and parapets. The replacement of them by means of lightweight solutions would considerably improve their seismic performance. In the Figure 1 an example is shown.

- Local modification of components
Local modification of components in case of structural insufficient capacity needs to be taken into account. This often leads to an enhancement in connectivity, strength and deformation capacity as shown in Figure 2.

- Increasing building strength and ductility
When elements show an inadequate ductility, enhance their strength will increase the elastic threshold, reducing the necessity of ductility (Figure 3). If, on the other hand, ductility is supposed to be increased, the use of ductile material is required. This replace of brittle material in strategic elements allows large deformations within critical limits whilst retaining the element capacity to withstand the gravity force.

- Reduction of irregularities in plan and elevation
Key aspects are represented by symmetry and regularity in both plan and elevation. Especially plan irregularities, such as annex garage, can trigger torsional moment in the connection. In this situation the building can be separated, or a flexible connection can be adopted.

- **Introduction of energy dampers and base isolation**

Every structure possesses inherent damping. An increase of energy dissipation can be realized by the addition of energy dissipating devices such as hydraulic cylinders (Figure 4) and yielding plates. Moreover, the energy dissipation can be achieved by disconnecting the building from the ground. This can be realized by the installation of special connections between foundations and elevation elements able to increase the building period.

5. **Upgrading strategies**

For the Groningen building stock measures of preliminary structural upgrading related to the weakening aspects have been formulated. The measures have been thought in order to satisfy both life safety and damage mitigation. Particular attention has been given that during the realization process social disturbance will be minimized, and the final result will show the slightest possible aesthetic incongruences.

The upgrading measures for both structural and non-structural elements can be distinguished in two categories of intervention. Temporary upgrading measures are intended to be applied on the URM building stock which requires a rapid risk reduction. In the case of a high vulnerable building, an external stiffness upgrade, which supports laterally the building can be considered a short-term risk mitigation until a permanent measure has not been developed.

Permanent measures have been divided in seven levels as recommended by ARUP on behalf of NAM in the report *Groningen 2013 Structural Upgrading Strategy*[8]. The levels are ordered from 1 to 7 regarding the efficiency of the measure and the rapidity of completion respect to the risk mitigation, but also taking into account the inhabitant repercussion. The rising of the measure level aims to highlight the increment in complexity, duration and people impact.
6. Existing retrofitting techniques

On the basis of the achievable improvements in structural performance of the buildings, described in the previous chapters, a brief overview of the existing seismic upgrading techniques follows. The aim of this chapter is to list a series of solutions presently used in areas of earthquake hazard, which can be adapted to the Groningen building stock.

6.1 Techniques aimed to improve structural connections

These interventions result to be adequate for favoring a monolithic three-dimensional behavior of the structure in the meaning of wall-to-wall and floor-to-wall connection and to contain lateral loads from the roof.

- Metallic or different material tie-rods
- External circumferential bandage
- Local connections between walls and diaphragms

6.2 Techniques aimed to increase the floor slab stiffness

These solutions aim to guarantee the load transmission by the floor to the walls in the same direction of the seismic action. Furthermore they also represent a restriction against the wall overturning due to horizontal perpendicular loads.

- Timber second panel above of the existing timber floor
- Composite material strips (FRP strips) fixed on the existing panel diaphragms
- Steel truss system below the timber floor
- Reinforced concrete topping overlays above of the existing timber floor

6.3 Techniques aimed to extend out-of-plane strength

Even when the diaphragms are well connected to the walls, the horizontal forces acting in the out-of-plane direction of the wall can cause a significant bending moment. The bending moment resistance of the wall is determined by the ratio of the height between levels of support and the thickness of the wall itself, in addition of the axial load. In order to increase the bending capacity, some techniques are nowadays used:

- Vertical inter-floor support
- Horizontal inter-floor support
- Post-tensioning steel rods inserted into vertical holes drilled through URM wall
- Non-stressed bars inserted into vertical holes drilled through URM wall and bonded with mortar
- Composite material strips (FRP strips) fitted into vertical saw cuts in URM
- Steel strapping

6.4 Techniques aimed to increase in-plane strength

When the in-plane capacity of the wall results to be exceeded by the seismic loads, these retrofitting interventions are needed in order to increase the in-plane wall flexural and shear capacity and to adding ductile properties.

- Overlay concrete shear walls (jacketing)
- Composite fiber reinforcement (FRP strips)
- Steel exterior or internal elements
- Exterior or internal axial post tensioning
- Horizontal bars bolted through washer

6.5 Techniques aimed to upgrade the foundation strength

Foundations in existing URM buildings often result to be adequately designed to resist seismic events. However extra loads can induce significant vertical load, due to the presence of additional components applied for the retrofitting of the other structural elements.

- New concrete footing besides old footing tied with drilled reinforced rods.
- Tying of foundations together with ground beams
7. Seismic retrofit design-approach

The seismic retrofit of a building is normally based on one of two design approaches, namely Damage Limitation Retrofit (DLR) and Near Collapse Retrofit (NCR).

7.1 Damage Limitation Retrofit

It represents the conventional engineering approach for seismic retrofit. The design is based on the strengthening of the structure vulnerable to aspects, such as connections, diaphragms flexibility and wall resistance. The design approach assumes the elastic behavior of the building, and focusing on different techniques aims to delay cracking. The retrofitting techniques must enhance the strength of structural elements, assuring the resistance necessary to withstand the forces generated by the elastic response of the building during the ground motion. Generally, the required resistance is calculated on the design-level earthquake, while in case of major earthquake, the additional energy will be assumed as dissipated by the post elastic deformation of both the material and connections. In case of upgrading the out-of-plane capacity of a wall, DLR approach would introduce vertical pre-stressed tie rods inserted into drilled holes. This will increase the axial load in the masonry wall element decreasing the formation of cracks during the seismic event.

7.2 Near Collapse Retrofit

NCR reduces the risk of severe structural damages and avoids the collapse after the post-elastic behavior has occurred. The design is related to the overall performance of the structure by means of structural stability during the post-yielding phase. This approach requires a good understanding of the dynamic characteristics of the structure in order to develop adequate interventions that prevent severe damage or collapse. In comparison to the previous example, regarding the lack of out-of-plane capacity of a URM wall, a NCR intervention would prevent the overturning of the element. This could be obtained by means of vertical fiberglass rods which, introduced into drilled holes, come into play only when the structure has developed cracks and has displaced enough to engage the stabilizing elements. Measures for a NCR provide a reduced response of the building by increasing the structural damping via friction across the cracks and by lowering the response frequency due to the wall rocking.

The two design strategies are not intended to be mutually exclusive, contrary they can be complementary. The DLR approach addresses the elastic performance of the structure, while the NCR approach addresses the post-elastic behavior.

The difference in the seismic damage behavior of the two design strategies can be better understood by the graphic representation in the Figure 5, which refers to a generic masonry building. In the graph the horizontal axis is an increasing function of earthquake intensity, whereas the vertical axis indicates the damage index.

The line represents different building performance:

- Line ABC depicts the performance of the building in its original condition
- Line DEF represents the damageability of the structure with a Damage Limitation Retrofit
- Line GHI represents the damageability of the structure with a Near Collapse Retrofit

Point A represents the threshold earthquake intensity for the damaging of the masonry building. When the point A is reached, the increasing in the earthquake intensity will produce an increment of the reparable damage, which is limited by the point B. The line between B and C represents the non-reparable damage, and it ends in point C with the collapse of the building.

A classic DLR has the effect to translate the threshold of initial damage. The distance between point A and D shows the improvement produced by the upgrading of the building. Once the seismic intensity overruns

![Figure 5 Plot of damage-progression index versus earthquake severity for non-retrofitted structures (ABC) and for DL (GHI) and NC (DEF) retrofitted structures. Tolles et al. [9]](image-url)
following the line until the point E. It can be understood from the graph that, once the strengthened additions on structural elements and connection fail (line E-F), the behavior of the structure as a whole becomes dominant. Collapse occurs on F, which is reached by a little increment in the seismic intensity respect to E. In the case of a NC retrofitted structure, the point of initial damage G corresponds to a small increment of earthquake intensity respect to the non-retrofitted structure, point A. This is a consequence of the fact that no attempts have been done to avoid cracks. Indeed, this strategy adopts the non-linear behavior as advance, focusing on displacement constraints, instead of strength improvements. The yielding of the material and bonds advances to point H, where the overall behavior starts to dominate the performance. After the point H, the stabilization retrofit elements are activated, and the structure shows an increasing rate of repairable damage. The point I indicates the limit of relative high earthquake intensity for which the structure does not collapse.

In conclusion, while a DLR results in a better damage control at lower earthquake intensities, the NCR aims to life-safety and preventing collapse.

8. Conclusions
The Groningen case represents a real research challenge in terms of URM house building seismic retrofitting. This situation involves designers to analyze state of art of upgrading URM structures in order to define the best technically reliable solutions for each case. The idea is to provide a standard guide able to furnish practical solution for the first 5 levels of the structural upgrading strategy. The guide will be based on the typology of building mostly present in the area. The appropriate solution will be carried out by a screening of existing techniques and innovations, a series of parameters will lead to the most technically reliable approach.

- Structural efficiency
- Aesthetically acceptable
- Minimal disruption during execution
- Scalability
- Repeatability
- Economically suitable

The selected solutions will be clearly explained by technical sketches and practical informations for the building process. Examples of calculation design will be provided based on conventional URM house building components.

9. References