Innovative systems for earthquake resistant masonry enclosures in RC buildings

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ABSTRACT: The Commission of the European Communities has recently funded a research project for the benefit of Associations of Small and Medium Enterprises (SME-AGs), aimed at developing innovative systems for masonry enclosures. More in general, the project deals with external partition systems for reinforced concrete framed buildings, such as infill walls and envelopes, and with internal partitions. The project involves sixteen partners from seven European countries, among which there are seven universities and research centres, five industrial associations, and four small and medium enterprises. In the present contribution, an overview of the main objectives and steps of the project is given. A general summary of the various construction systems that are being developed and designed is given. The future developments in terms of experimental programs, numerical analyses, and final expected outcomes of the project are described.

Keywords: Clay masonry infill walls; combined in-plane/out-of-plane behaviour; experimental testing; numerical modelling; design procedures

1 INTRODUCTION

INSYSME is the acronym of a Research Project for the benefit of SME Associations with a budget near to 2.7 millions of Euro, co-funded for about 1.8 million of Euro by the European Commission [1]. The INSYSME project clusters 16 Partners, representatives of Universities, Industrial Associations and SMEs from 7 European Countries. The head of the project is the Department of Civil, Environmental and Architectural Engineering of the University of Padova. Among others partners involved in the project there are the University of Minho and the Technological Centre of Ceramics and Glass in Portugal, the Universities of Pavia in Italy and Kassel in Germany, the Middle East Technical University in Turkey, the National Technical University of Athens in Greece. The involved SME Associations are ANDIL in Italy, ZIEGEL in Germany, APIKER in Portugal, TUKDER in Turkey, and Tiles & Bricks Europe (TBE). The Small Medium Enterprises are active in different fields: Ruredil S.p.A. is an Italian manufacturing company that ranges from chemical admixture to mortars, SDA-Engineering GmbH is a German company active in the fields of structural engineering and software development, Xalkis S.A. is a Greek manufacturer of clay tiles and bricks, SCI H.I. Struct s.r.l. is an engineering firm settled in Timisoara, Romania.

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The project aims at developing innovative systems for a wide range of masonry enclosures, by improving their overall technological performances and in particular those related to the earthquake behaviour. The project also aims at developing sound design rules, in order to update national and European standards and to make engineering design easier and more reliable. To reach these goals, the project is structured into two main steps, in a three-year time. In the first step, new construction systems for enclosure walls will be developed, and their technical and economic feasibility will be assessed performing parallel experimental and numerical studies. The progress towards successful completion of this phase will constitute a milestone for the subsequent project prosecution. In the subsequent step, on the basis of the obtained experimental and numerical results, design methods for this kind of elements will be developed, and the proposed solutions will be completely validated by demonstrations of design and construction of prototype walls in real buildings. Procedures for quality assessment through on-site testing, software for design and guidelines for end-users, will ensure full usability of the developed knowledge and technologies.

The technical program has been organized according to this research approach (Figure 1). It is organised in 7 interactive Work Packages (WP) and its RTD core foresees the definition of a set of technological constructive combinations (WP3), that will be tested on multi-scale levels (WP5) and on which various modelling strategies and types of analysis will be applied in order to provide reliable calculation rules (WP4). The outcome of the research will be the development of fully constructible and economically feasible innovative systems. The achievement of this goal is ensured by WP6 (Demonstration of constructability) and will find application in the tools and design guidelines given in WP7, which will thus constitute the final research objective.

![Figure 1. Pert Chart of the INSYSME Project](image)

## 2 MOTIVATION OF THE PROJECT

The use of masonry infill walls and, to a certain extent, veneer walls, especially in reinforced concrete (rc) framed structures, is widespread in many countries. Indeed, masonry enclosure systems contribute significantly to the performance of buildings, in terms of healthy indoor environment, temperature, noise, moisture, fire, durability. They prevent unpleasant micro-environmental phenomena, which cause problems of comfort, aesthetics, and durability, to occur. Hence, the total
cost of the building (initial cost plus maintenance) is reduced [2]. However, the widespread use of non-load bearing masonry enclosures in rc frames is accompanied by a series of drawbacks, including structural problems. This is particularly pronounced when the so-called “non-structural” elements are subjected to actions that force them to behave structurally, as in the case of earthquakes. Indeed, today design provisions for ductility and proper detailing can ensure that framed buildings behave properly under earthquakes. Notwithstanding, the shortcomings of masonry enclosures when subjected to seismic loads are not yet solved, as modern earthquakes confirm.

The Loma Prieta (1989) and Northridge (1994) are good examples of the economic costs associated to non-structural damage (30 million USD dollars), even in buildings that were not structurally affected [3]. In Lefkada (Greece, 2003, Mw = 6.2), where only one reinforced concrete building collapsed, damage was mainly related to cracking of infill walls and reported injuries were mostly related to free-falling roof tiles and infill wall units [4]. The 2009 earthquake in L’Aquila (Italy, Mw = 6.3) produced around 300 casualties and more than 1500 injuries. Indeed, rc building structures behaved, on average, fairly well, despite the severe ground shaking. However, widespread extensive damage to masonry infill and internal partition walls was detected, and caused the highest losses in rc buildings [5]. The 2011 earthquake in Van (Turkey, Mw=7.1) once again demonstrated the highly variable nature of the seismic damage to infill walls in rc frame buildings, where in some cases (Figure 2a, b, c), infill walls contributed significantly to strength and hence helped in the survival of the building, whereas in some other situations (Figure 2d), masonry infills detached from the structure and/or collapsed due to a combination of in- and out-of-plane demand. This type of non-structural damage can be extremely dangerous for occupants. Also in the recent (May 2012) earthquake in Emilia (Italy, Mw=6.0), examples of in-plane and combined in-plane and out-of-plane masonry infill and veneer damage have been reported (Figure 3). Problems related to the performance of masonry infill and veneer types and construction techniques, typically adopted in Italy and other seismic prone European countries, could be identified, even in newly constructed buildings [6].

Figure 2. Damage to infills in 2011 Van Earthquake: a) in-plane damage, b) damage inside building in a, c) moderate damage, d) heavy combined damage

Figure 3. Masonry infill and veneer damage: Emilia, Italy, 2012
In this context, most of the codes have recognized that also non-structural elements need to be designed for earthquake actions, in relation to different performance levels. However, sound design procedures still do not exist. In the current design practice in Europe, referring to the design of new buildings, rc frame structures subjected to seismic loads are usually examined using linear elastic structural models on which equivalent static or multimodal dynamic response spectrum analyses are performed. The design of infilled rc structures is usually performed on bare frame elastic structural models; where the masonry infill panels are considered in terms of masses and vertical loads only. In this context, the safety verification of rc frames at the ultimate limit state, according to Eurocode 8 [7], has to be accomplished in terms of resistance to seismic action effects for both structural and non-structural elements. In particular, for non-structural elements like interior and exterior walls, partitions and facades that might, in case of failure, cause risk for human life or affect the main structure of the building or services of critical facilities, the verification of resistance for the design seismic action is foreseen and a simplified procedure is proposed for the evaluation of the horizontal seismic force acting on the non-structural element. Nevertheless, in Eurocode 8 no recommendation for the calculation of the corresponding resistance of the building enclosures is provided. Moreover, the damage limitation requirements for buildings with non-structural elements are considered satisfied when the induced inter-storey drifts do not exceed certain limits in each storey of the building, defined only as a function of the “ductility” of the infills and on the connection with the surrounding structure, without any reference to the type of masonry enclosure and to the dimensions and amount of infills.

As regards the technological aspects, some measures for new infill walls are mentioned in Eurocode 8, such as light wire meshes well anchored on one face of the wall, wall ties fixed to the columns and cast into the bedding planes of the masonry, and concrete posts and belts across the panels and through the full thickness of the wall [7]. The first solution (light wire mesh) may raise doubts related to durability and external appearance, in particular, when traditional materials are used. Moreover, experimental validation of its effectiveness is limited to few specific types and thicknesses of infills [8]. The wall ties fixed to the columns solution give some possibility for development, although technological improvements still need to be achieved [8, 9]. The concrete posts and belts solution, if massive, is costly, invasive and gives rise to issues regarding the possible interaction effects with the concrete elements of the frame. Indeed, it is noted that, even the reinforcement of the infill, may lead to undesired behaviour. In fact, according to test results [10], and to observations after earthquakes (Figure 4), the RC tie beam at mid-height of the infill modifies the failure mode (from diagonal cracking to shear sliding along a horizontal joint). This is a failure mode that may adversely affect the behaviour of the RC columns, adjacent to the infill.

In addition, the empirical solutions proposed by the code are not accompanied by rationales for design, applicable to the various types of masonry enclosures, and not even rules for the use of connectors in composite systems such as masonry veneers are given. This unclear environment, the absence of clear performance requirements and design methods, and the lack of some practical (even if theoretically stated into the code) measures, discourages the use and the further development of masonry construction systems for enclosure walls. Hence, the further development of code requirements for seismic design of infilled rc structures, as well as the introduction of practical solutions which allow achieving satisfactory levels of damage limitation and life safety, is of primary interest and represents the main goal of the INSYSME research project.
PROJECT OBJECTIVES

Infill masonry panels, if properly distributed and considered in the seismic design of structures, can have a beneficial effect. They increase the stiffness of the structure, result in reduced displacement demands, and contribute to the dissipation capacity of the structure, offering significant extra shear resistance to the earthquake. Hence, for existing rc buildings, constructed before the advent of current seismic codes, severe damage or even collapse can be attributed to poor original design or deficient construction detailing \[1\]. In some other cases, damage and collapse of rc buildings is caused due to improper consideration or neglecting of the influence of infill walls on the surrounding rc elements. One cause of adverse effects is associated with the infills leaving a short portion of the column clear. In addition, the irregular arrangement of infill walls along the height of the building causes an abrupt change of the building stiffness, resulting in the possible activation of soft-storey mechanisms. Moreover, the asymmetric distribution of the infill masonry walls on the building plan can introduce torsional effects, and hence, induce large displacements of rc columns \[12\].

Under accidental actions, such as earthquakes, deficiencies of the enclosures themselves (infills and veneers) may be significant. Indeed, masonry enclosure walls mobilize their maximum in-plane resistance for small values of imposed shear deformation, usually with the appearance of shear cracking. Their response is rather brittle, characterized by a decrease of resistance for larger values of shear deformation imposed by the frame during earthquakes, thus resulting in severe damage, possibly even disintegration or partial collapse of the wall. In addition, infill and veneer walls detach from the surrounding frame elements at early stages of the seismic event and they can collapse out of their plane. Thus, they may cause injuries or even casualties and they become the main cause, disproportionate and unjustified, of damage to property, as highlighted by recent earthquakes \[e.g., 4; 5; 13\]. This phenomenon is unfavourable also because it requires extensive repair, or demolition and reconstruction, associated with major time consumption and high costs. The INSYSME project will find solutions to reduce the drawbacks related to the use of infill and veneer walls in rc frames, still exploiting their beneficial effect on the overall building behaviour.

3.1. Development of materials and technologies

Several recent research programs have focused on the development of strengthening techniques for existing and possibly damaged infills, aimed at improving both the in-plane and out-of-plane performance (e.g. Figure 5, left). Various techniques for the retrofitting of unreinforced masonry walls have been introduced, namely pre-stressing, jacketing and surface treatments. More recently the application of innovative materials, such as fiber reinforced polymers (FRP) and steel reinforced grouts (SRG), has been also proposed. Today, these techniques have been largely tested; they have been even introduced into several guidelines for the retrofit and strengthening of existing buildings, and are being applied for the repair of damage induced by recent earthquake \[14, 15, 16, 17\].
However, surprisingly enough, no substantial research efforts have been done for the development of improved solutions for new construction of masonry enclosure walls, and the evaluation of damage to masonry infills themselves has been only recently more widely recognised in the earthquake engineering community. Specifically in the European context, within the scope of the on-going SERIES research project, two prototype masonry infill typologies, i.e. a traditional and an innovative type of infill, have been addressed [18]. Improvements in the seismic response of the masonry infills have been reported based on preliminary results due to the application of enhancement techniques (i.e. bed joint reinforcement) [19]. In another research program, infill walls reinforced either by a tie-beam at mid-height or by bed joint reinforcement were tested under in-plane and out-of-plane actions independently [10]. As long as it regards the out-of-plane behaviour of the infill walls, the tests have proven that the addition of an RC tie-beam (Figure 6), or of bed-joint reinforcement, does not lead to an increase of the maximum load. However, bed-joint reinforcement allows for high out-of-plane deflections, without disintegration of the wall. Within the DPC-RELUIS 2010-2013 project, a series of numerical analyses based on models calibrated on existing test results have been carried out, resulting in implications for the design of new rc frames with masonry infill [20], and an experimental research program related to the combined in-plane and out-of-plane response of several clay masonry infill typologies (Figure 5, right) has been accomplished [21]. The research results indicate that satisfactory in-plane and out-of-plane infill performance can be achieved through the application of enhanced construction techniques and design approaches. Enclosures with deformable joints, leaving an empty space between the infill and the frame elements, aim to minimize the infill-structure interaction. In these systems, the use of e.g. shelf angles for guaranteeing out-of-plane stability is often proposed. In this case, problems of durability, aesthetics, and indoor comfort arise. Very recently, masonry infills with frictional sliding fuses, that increase their in-plane deformation capacity, have been proposed [22]. However, the out-of-plane behaviour of such systems, which is subdivided in several horizontal portions, has not been taken into account.

Most of the patents in international databases are related to thermal insulation units for enclosures. There are also many patents of construction systems for structural masonry and claddings, and for seismic strengthening of existing infill walls. Only few patents are related to construction systems for new seismic enclosure masonry walls. Some solutions refer to the use of embedded horizontal and/or vertical reinforced concrete elements, cast within masonry cavities. Other solutions refer to the use of FRP units, joined with resins, and connected with embedded elements in the horizontal joints all along the frame. The only solutions that are in line with the proposed research project relate to the development of special masonry ties for cavity wall construction and veneer walls. In this field, “structural veneers” have been recently developed in the US. These enclosures are made of hollow clay or concrete units, cast with concrete and reinforced, and are attached to the frame with few robust anchorages. By doing so, veneers and frames can have independent relative horizontal displacements, thus avoiding in-plane damage [23].

Figure 5. System for external reinforcement of existing infill walls (left) and reinforced masonry system for new clay unit masonry infill wall (right) tested at the University of Padova
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The principal objective of the project is thus to develop optimized masonry enclosure solutions for enhanced earthquake resistance, respecting local materials and construction practice, and considering the various levels of seismic input and environmental requirements related to the different countries. Possible types of innovative masonry enclosure systems to be developed, with reference to materials and construction details, may be divided in three major groups: (i) systems built of conventional components, following original design methods, (ii) systems built of conventional components and applying sophisticated enhancement techniques (e.g. through application of reinforcement, connectors/fasteners, joints, angles, shelves), following original design methods, and (iii) systems built of innovative components (such as clay masonry units of particular shape, sliding mortar, various steel components), following original design methods. Solutions related to various constructive types and conceptual design will be considered, in particular, (i) enclosures included in the frame, and rigidly attached to it (rigid infill), (ii) enclosures included in the frame, allowing relative displacements between the wall and the frame (separated infill), and (iii) external enclosure systems, attached to the frame or to backup infill walls, having the possibility of controlled relative movement (veneer walls). It should be noticed that the developed solutions should refer to integrated, but easy to be built and cost-effective systems, so as they can be commercialized and largely applied in constructions.

3.2. Modelling seismic response of rc frames and enclosures

The problem of the wall-to-frame interaction, i.e. how the enclosure systems modify the response of the structure inducing a positive, or more often a negative, effect, has been object of many studies and researches [e.g., 8; 24]. Many studies also concentrated on how the infill wall effect should be modelled to reproduce the stiffening effect of masonry on the frame. This can be made by using equivalent struts, able to reproduce the various in-plane failure modes of the walls: compressive failure at the centre of the wall or at the wall corners, failure for sliding shear, shear failure with diagonal cracking. Struts elements have been created for both non-linear static analyses and, introducing hysteresis rules, also for non-linear dynamic analyses [24]. However, although the today's software allow for infills to be considered in the design process, they are most often neglected, and design of rc framed structures is simplistically carried out, most of times, on the bare frame, or according to still inconsistent rules.

Further on, and most importantly, until today research work, and in particular numerical analyses, have focused on the effect that enclosure systems have on the structural frame response, yielding to the above-mentioned, although still not final, rules. However, the reverse problem, i.e. how the structural response of the frame influence the behaviour of the infill, has been to some extent recognized only in few recent initial studies [21; 25]. Only a very new and recent model can combine in- and out-of-plane deformation limit states for the definition of the masonry infill strut elements [26]. Hence, the numerical and experimental work of the project will mainly focus on this latter, almost unexplored, aspect, with the aim to provide original integrated solutions with respect to the choice of...
materials, design, detailing and construction, for a wide range of earthquake resistant masonry enclosures, addressing both in- and out-of-plane damage control.

Some of the aspects to be defined by modelling and numerical analysis are the drift equivalence between bare and infilled frames, as already proposed, for weak infill walls, by [25]. This would allow combining the simplified design of infilled rc structures on bare frame elastic structural models, as already mentioned in section 2, with a more realistic consideration of the presence of the masonry infill panels. The definition of seismic input, which is necessary for the design of the infill walls and veneers, can be also investigated by means of linear and non-linear dynamic analyses. Indeed, a formulation for its calculation has been recently introduced in some structural codes in Europe [7; 27]. However, many national codes still do not have such information [28], and, if we compare our codes to those available in other non-European countries [12; 28; 29], we can see that there are significant differences in the approach, bringing to some doubt on the validity of the various methods. Indeed, recent dynamic analyses [30] demonstrated the inconsistency of the proposed approach with the actual out-of-plane response of masonry walls. In addition, the systematic parametric analysis of different types of infilled rc frames, could be used for evaluating the effectiveness of the new proposed infill wall solutions in strengthening existing structures, and for probabilistic risk assessment.

3.3. Experimental/numerical testing of combined in-plane/out-of-plane behaviour

A key aspect related to the influence of the frame behaviour on the infill is that, during an earthquake, infill walls are subject not only to out-of-plane actions but, at the same time, also to in-plane actions caused by the deformation of the frame. Because of masonry limited shear strength, the damage caused by the in-plane deformation of the frame, causes a reduction in the wall out-of-plane strength. Very few studies have considered an experimental definition of infill limit states based on the frame inter-storey drift [e.g., 8]. The numerical studies carried out so far have never systematically tackled this aspect, too. Indeed, very few studies have addressed the definition of limit states of infills based on frame inter-storey drift [20; 25]. No methodical definition has been achieved to quantify how the extent of in-plane deformation of the frame influences the mechanical properties in the enclosure systems and, consequently, the out-of-plane response. Therefore, in the project, extensive numerical simulations, mainly using non-linear static analyses, will be aimed at studying this aspect.

Understanding the combined in- and out-of-plane behaviour of clay unit infilled RC frames requires experimental evidence to establish deformation limit states and to validate seismic performance of new technologies. Since the early studies on infilled frames, in fact, lot of experimental tests were carried out for evaluating the influence of different types of walls on the in-plane stiffness of the frame [24]. Commonly, tests were performed on one-bay, one-story frames, filled with various masonry walls, subjected to increasing quasi-static in-plane displacements, on both real-scale and reduced scale frames [e.g., 31]. Some experiments were carried out in presence of openings, having different length to height ratios also in relation with the frame geometry, to investigate the effects of openings on the in-plane behaviour of the infill and calibrate the corresponding models [e.g., 32]. Conversely, the combined in- and out-of-plane behaviour of infills, aimed at assessing the influence of the in-plane infill damage on the infill out-of-plane response, has been experimentally reproduced only in few very recent studies [8; 21; 33; 34]. As an example, see the test set-up of Figure 7. In the INSYSME project, the achievements from recent studies will be exploited and further developed, so as to: (i) derive an adequate testing methodology, concerning reference rc frame, in-plane displacement history, out-of-plane loads application method, quasi-static or dynamic loading procedure; and (ii) carry out tests on a large (differentiated) number of clay unit infill walls, taking into account the various technologies developed in the project framework.
Besides these quasi-static combined tests on single bay structures, also dynamic shaking table tests will be carried out on at least two model buildings, with the use of at least two enclosure systems developed during the project and some solutions of partition walls. These tests will constitute the real validation under dynamic loads of the adopted solutions. Indeed, some shaking table tests of infilled rc frames have already been carried out in the past, with the aim of studying the effect of infill walls on the frame [13], or examining the out-of-plane behaviour of the enclosure walls [35], and focusing in particular on the effect of retrofit measures for the infills. The tests to be carried out in INSYSME, besides being necessary for corroborating the new construction systems, will have a different approach. Particular importance will be given to studying in detail the dynamic response of the infills in relation to the dynamic behaviour of the frame. The envisaged contribution is of particular importance for solving the problem of combined influence of in-plane and out-of-plane damage. The results will also be applied for calibrating models and defining the seismic input on the enclosures.

3.4. Rules for verification of enclosure walls and guidelines

Based on the numerical analyses and experimental tests carried out, introduced in previous Sections 3.2 and 3.3, it will be possible, first of all, to define the structural performance requirements of non-structural elements on the basis of the overall performance levels defined for the building. The experimental and numerical work will lead to the development and calibration of formulations and procedures for out-of-plane verification. Indeed, in those countries where recent seismic events have highlighted the vulnerability of the infills, the codes have introduced their mandatory assessment. As an example, the Italian code [27] requires that, excluding only internal partitions having thickness smaller that 100mm, the non-structural elements that may endanger people, must be verified together with their connections to the structure. Hence, once the seismic input has been defined, it should be stated how to apply this action on the enclosure walls and it is necessary to properly define the wall capacity. At this regard, besides the US guidelines for evaluation of earthquake-damaged buildings [29], the codes do not suggest any particular procedure. It has to be reminded that the values of out-of-plane capacity that can be defined on the basis of the sole section modulus and flexural strength are rather low and conservative [36]. For the verification, it is possible to consider a static scheme with the formation of a resisting arch in the masonry thickness, in analogy with proposal given by the codes for load bearing masonry [37]. However, it is also necessary to consider other aspects, such as the non-adherence of the wall along the rc frame extension, the possible activation of different resisting mechanism, also depending on the masonry thickness, or the influence of in-plane damage on the masonry mechanical properties.

These aspects will be numerically studied within INSYSME, to reach a reliable calculation of out-of-plane infill wall capacity on the basis of the frame in-plane drift, and to formulate simple rules and
procedures for design. Cleary, due to the interaction of in-plane and out-of-plane response, the clear definition of a design procedure, accounting for the displacement capacity of the enclosures during the design of the rc frame, accepting the evident fact that the choice of the type of enclosure has to be accomplished in function of the level of seismicity, contributes to the innovative character of the envisaged outcome of the project. It is also worth noting that the current codes do not set clear rules for the design of connectors and anchors of cavity and veneer walls. As an example, if we take into account some proposals in the literature and by different codes [37; 38], it can be easily seen than the calculated axial force on connectors may vary up to 250%. In addition, most codes give very low values of connectors/m² [37], regardless of the wind and earthquake zones. The codes do not even provide performance requirements for serviceability limit states of veneers, that in principle could be even more restrictive than damage and ultimate limit state requirements, due to the necessity of preserving as much as possible the external appearance of the brick walls. In the case of the more advance structural veneer solutions, the definition of the in-plane behaviour (e.g., as a shear wall or a deep beam) is also a pre-requisite for safe design of enclosure systems. Therefore, through numerical analyses, INSYSME will also provide sound construction details and rules for veneer walls.

4 CONCLUSIONS

In the present contribution, the main objectives of a recently funded EU Research Project, aimed at developing innovative systems for enclosure walls in framed reinforced concrete buildings, have been presented. The main objectives related to the development of enclosure masonry systems, to their experimental testing, to the numerical modelling of overall frames and of the single walls, and to the development of simple rules for optimized design, have been presented. The construction systems that are being studied and developed by the partners cover most of the seismic hazard levels and environmental conditions of the various European countries. At the current stage, the construction details of the various envisaged systems are being defined, and the experimental tests phase will start in the next few months.

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