Developing Innovative Systems for Reinforced Masonry Walls

by

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ABSTRACT

The Commission of the European Communities has recently funded a CRAFT research project aimed at developing innovative systems for load and non-load-bearing reinforced masonry walls. The project involves twelve partners coming from four different European countries, among which there are universities and research centres, small and medium enterprises for the production of clay and concrete units and mortars, a company for advanced metal products and industrial associations of brick and block producers.

The development of the reinforced masonry walls is based on the advancement of vertical reinforcement and fastenings, of mortar and concrete and on their integration with special clay and concrete blocks for the definition of new construction systems. The foreseen advantages are: new possibilities for masonry; more economical construction; quality increase for masonry walls; crack-free and earthquake resistant construction. The project follows three steps: assessment of the technical and economical feasibility of the envisaged construction technologies by means of extensive experimental and numerical activities; construction of prototypes as demonstration of the proposed technologies and materials; in situ testing to completely validate the systems.

In the present contribution, an overview of the main objectives and steps of the project is given. Furthermore, the different construction systems that are being developed and designed are described. The main fields of application and the main technical problems encountered for the different construction systems is described, together with the experimental program outlined in order to characterize their mechanical behaviour under different serviceability and ultimate conditions.

1. INTRODUCTION

DISWall is the acronym of a Co-operative Research Project with a budget near to 1,340 millions of Euro, co-funded for about 1 million of Euro by the European Commission [1]. The project, that will last 24 months, aims at developing innovative systems for reinforced masonry walls. The DISWall project clusters 12 Partners, representatives of the Universities, SMEs and Industrial Associations from 4 Countries of EU. The head of the project is the Department of Structural and Transportation Engineering of the University of Padova. Among others partners involved in the project there are the Universities of Aachen and Munich from Germany and the University of Minho from Portugal. The involved Small Medium Enterprises are two Italian clay blocks manufacturers, CIS Edil Srl and ALAN Metauro Srl, a German clay blocks manufacturer, UNIPOR GmbH; a Portuguese concrete blocks producer, Costa & Almeida Lda; the Italian mortar manufacturer Tassullo SpA and, finally, the Belgian company BEKAERT N.V. that produces steel wire, used as vertical and horizontal reinforcement in masonry construction. ZIEGEL and ANDIL Assolaterizi, representing respectively the German and Italian clay bricks industry, are the Producers' Associations of that joined the project.

The main scientific and technological objectives of the DISWall project are: i) to carry out theoretical studies of the properties and the requirements for masonry units, reinforcement, mortar and concrete for construction of reinforced masonry systems; ii) to develop innovative technologies and building processes for the construction of load-bearing and non-load bearing reinforced masonry walls; iii) to design, manufacture and test the developed prototype products; iv) to validate experimentally the envisaged technological solutions by purpose-designed testing procedures and to carry out numerical parametrical assessments to define critical mechanical parameters and to assist the optimization of design; v) to carry out theoretical studies of Non-Destructive Evaluation methods to assess the masonry structures and to calibrate the relevant parameters on laboratory specimens and subsequent on-site applications; vi) to develop design rules for the proposed innovative construction systems and for their implementation into software tools and guidelines; and, finally, vii) to transfer the research results into Regulatory and Standardisation Technical Bodies in order to include them into the Structural Codes.

The achievement of these objectives will come by research, technology and development activities arranged into five basic work packages: WP3 - Product development, WP4 - Construction technology, WP5 - Experimental and numerical characterization, WP6 - Design of masonry walls, WP7 - Construction and testing of prototypes, and two parallel work packages, one devoted to management issues (WP1 - Project Management) and the other designed to carry out training and dissemination (WP2 - Dissemination and Exploitation). The seven work packages are all complementary and linked each other by a specific work programme, as can be seen in Figure 1. The description of and an update of the project results can also be found on the project web-site: http://diswall.dic.unipd.it.

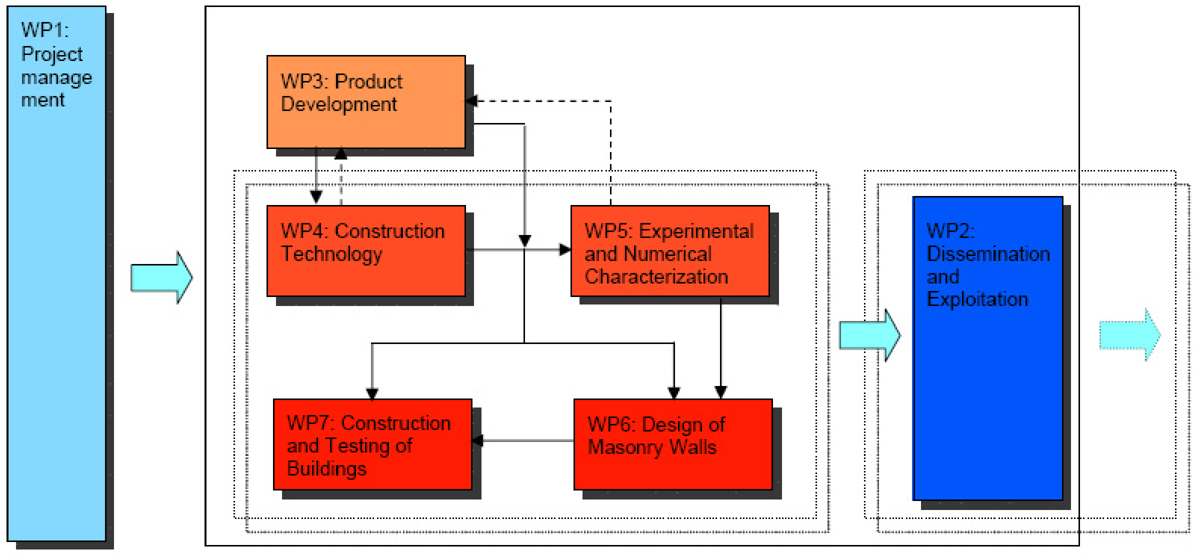


Figure 1 Pert chart of the DISWall project

2. OBJECTIVES OF THE INVESTIGATION

The construction of reinforced non-load-bearing and load-bearing masonry walls can be very effective in reducing damage due to cracking and in improving the seismic capacity of buildings while providing at the same time a satisfactory internal environment. Despite this, the use of incorrect materials and of out-of-date or complicated construction technologies and processes can lead to some defects that can completely alter the behaviour of the walls and can render useless the effects of the reinforcement [2-4]. This condition is made worse, in most of the European countries, by the unpreparedness of consultants and practitioners in the field of construction with structural materials other than steel and concrete (see, for example, the percentage use of different structural solutions for buildings shown in Figure 2).

The limitations rising from improper construction practice are dramatically increased by the use of dated design methods that do not deal with or have not been developed specifically for reinforced masonry systems, by the increased design loads for winds and earthquake in the new European and National standards [5-7] and, finally, very often by the lack of provisions in the codes on how to evaluate the serviceability conditions for non-load bearing reinforced masonry walls, although the serviceability state can provoke significant stress states [8]. Moreover, the lack of procedures for quality control of the masonry walls, besides the possibility of partially dismantling the same structures, makes it impossible to define and evaluate standard parameters against which to measure the quality of the final product of the construction process.

The definition of the innovative and more appealing reinforced masonry construction systems is being based on the knowledge of the existing ones. For this reason, preliminary studies about the basic requirements for masonry units, reinforcement, mortar and concrete were carried out, considering that the properties of the individual materials plus the interaction between these materials is of basic importance in defining the behaviour of a masonry wall as a composite material [2]. A database of experimental results was developed in order to classify, describe and characterize the different reinforced and confined masonry typologies on the basis of the results of previous experimental researches. This summarizes the main results obtained on the single masonry constituent (units, mortar and concrete and reinforcement) and on entire masonry panels.

In particular, the quality of reinforced masonry is affected by the robustness of the blocks, as recent studies address [4], deriving from the equilibrium between the geometric shape, the percentage of holes, the thickness of the shells and webs and the quality and quantity of the constituent materials of units. A strong importance has thus been devoted to unit design. Moreover, the geometric shape of the units seems to be of basic importance, since it directly affects the construction system. Hollow units allow the placement of the vertical reinforcement into the large holes of the blocks which are subsequently grouted; perforated units are more similar to an unreinforced masonry construction system, and the joints are made step by step, as in ordinary masonry.

Regarding the mortar, the main issue is related to the possibility of using the same mortar both for the bed and vertical joint and for filling the cavities containing the vertical reinforcement. Therefore, workability and consistency properties are of basic importance. Furthermore, the improvement of bond properties, not only with steel reinforcement but also with the unit material, is considered to be an important issue, above all when special aggregates that decrease the bond properties are used to improve the thermal insulation of the masonry. For masonry made with large hollow units designed for concrete infill, the main issue consists in the incomplete filling of the holes [2], thus the use of special self-compacting concretes and special additives to overcome the problem is being studied.

Regarding the reinforcement, it is noted that horizontal reinforcement has already been developed into different types (from common steel bars to special trusses) that allows it to be applied in different masonry solutions. Conversely, vertical reinforcement has not been developed to the same degree, and in particular it is necessary to solve issues related to the anchoring in the top and bottom slab of the construction, possibly by means of special fasteners.

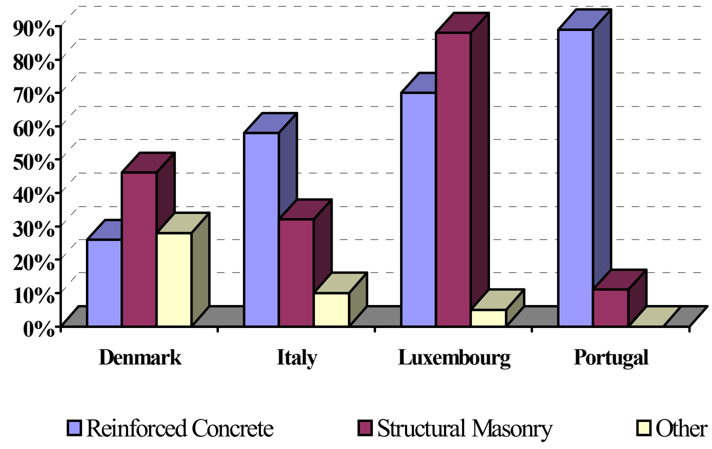


Figure 2 Comparison of structural solutions for buildings adopted in some European countries

Non-destructive evaluation techniques, including sonic and ultrasonic tests, impact echo, ground penetrating radar, infrared thermography, have been developed in particular for reinforced concrete structures such as civil infrastructures [9]. These techniques have been adapted and experimentally applied to historic masonry buildings, for the morphological characterization of walls and the identification of defects and inclusions [10]. Conversely, on modern masonry buildings only infrared thermography has been extensively applied [11], whereas other techniques for the localization of reinforcement, proper covering, corrosion and reinforced element properties have not yet been applied. The development and application of non-destructive evaluation techniques as methods for the quality control of reinforced masonry thus seems to be very appropriate and useful.

In this framework, the efforts made within the DISWall project are fully justified, as they are aimed at providing valid and complete innovative construction systems that ensure at the same time constructability, economic construction and maintenance, durability, good serviceability behaviour and high structural performance. They also solve the remaining technical problems and provide modern design methods that allow a simplified calculation of the masonry walls in order to propose safer, structurally sound, more appealing systems. Moreover, the project aims at solving the technical shortcomings of different types of structural and construction systems, in order to compete with the alternative techniques. Two types of walls are in fact considered in the project: (a) non-load-bearing masonry walls with application to medium to large span walls and (b) confined and reinforced load-bearing walls (Figure 3) with reference to seismic prone countries. Within these structural solutions, different construction systems are being studied. They are based on the use of perforated clay units, on the use of large hollow clay units for concrete infill, and on the use of concrete units, so as to cover the different masonry types used in the various European countries with respect to workmanship, execution techniques and materials.

3. CONSTRUCTION SYSTEMS BASED ON THE USE OF PERFORATED CLAY UNITS

3.1 Introduction

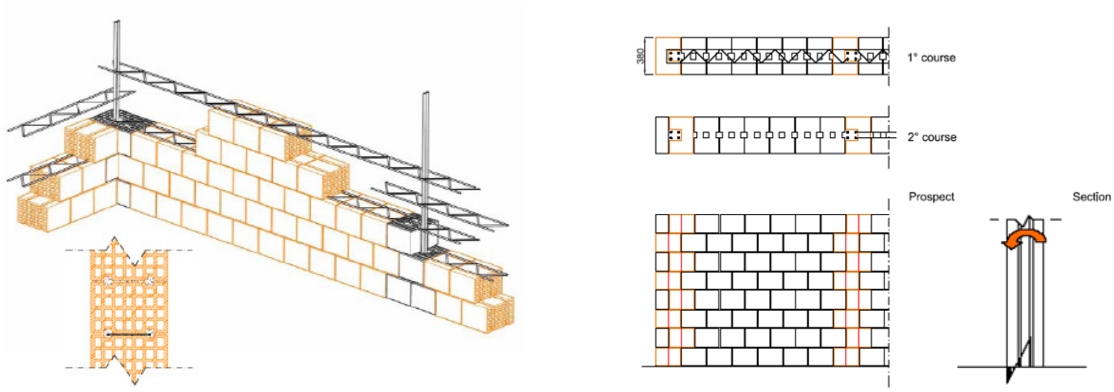
The most important issue that the masonry is currently called to face in Italy is related to the introduction of a more severe seismic code [7]. This problem will probably be shared by other European countries when the use of Eurocode 8 [8] becomes compulsory everywhere in the EEC. Within the DISWall project, two reinforced masonry systems made with perforated clay units typically used in Italy and designed for structural use (load-bearing masonry) are therefore going to be studied. They have been specially developed to withstand in-plane actions (for typical low-rise residential buildings) and out-of plane actions (for tall industrial buildings).

3.2 System for in-plane loading

The first system is based on the use of concentrated reinforcement, almost similar to a confined masonry system, made by using a special unit for the reinforced masonry panel and ordinary units for the reinforced masonry adopted to create the confinement columns. The units have to be placed in the masonry panel with horizontal holes, and they have to present recesses for the placement of the horizontal reinforcement (see Figure 4(a)). The width of the units is 300mm (but can vary between 200 and 350mm): they are mainly developed with square shape in order to be used in both directions in a second development of the same system with vertical holes in the masonry columns which will greatly simplify the common on-site procedures. The main advantages of the system are that all the problems related to cover of bars and mortar shrinkage are overcome due to the fact that there is a special recess in which to place the reinforcement, that it is possible to un-couple the reinforcement and that it is possible to preserve a construction technique (masonry made with horizontal holes) which is traditional for all the countries facing the Mediterranean basin, a technique which also allows very good thermal and acoustic insulation to be achieved. For this system, first of all the properties of the perforated clay unit need to be designed and studied, in particular the shape (geometry of the unit) in order to allow the creation of all the necessary structural details and a proper filling of the mortar that surrounds the reinforcement, and the mechanical properties of the unit (still related not only to the material properties but also to the shape of the unit), as the compressive strength and the robustness of the unit has to be enough to allow for a suitable behaviour when the masonry element is subjected to combined vertical and horizontal in-plane loading. The mortar will be a second topic of development, in particular for what influences the properties of consistency and plasticity, to allow for a proper joint (recess) filling, and the possible use of fibres or other additives in order to improve the bond with the bars and with the clay unit, as all the reinforced joints will be created on the external part of the shells which generally exhibit a less strong bond behaviour.

(a) (b)

Figure 3 Examples of structural masonry construction: (a) reinforced masonry; (b) confined masonry



(a) (b)

Figure 4 Construction systems based on the use of perforated clay units: (a) system for in-plane loading, units with horizontal holes; (b) system for out-of-plane loading, units with vertical holes

The main issue of the forthcoming testing program is to asses the in-plane cyclic behaviour of this kind of masonry wall. The specimens will be tested like cantilevers subjected to a constant and centred vertical load and to increasing horizontal displacements, with displacement peaks repeated three times for each displacement amplitude [12]. Each component of the system (the reinforced columns and the masonry panels) will be tested alone and combined together in order to check their interaction. The specimens will be tested by using normal uncoupled steel rebars and special steel trusses which can improve the on-site operations and the mechanical and durability properties of the masonry.

3.3 System for out-of-plane loading

The second construction system based on the use of perforated clay units that is being studied within the DISWall project is made by using perforated clay units with vertical holes developed and aimed at building mainly tall, load bearing reinforced masonry walls for factories, sports centres, etc.. In these cases, the use of slender load-bearing walls can be necessary, as they represent a technological solution with several advantages regarding structural and environmental requirements. A typical case is, for example, in the food industry, which requires the creation of an industrial working place where controlled thermo-hygrometric conditions must be kept constant. In this case, reinforced load-bearing masonry walls, compared to other solutions including framed structures, assure that those requirements are respected without the use of further insulating or coating materials. At the same time, the verification of the out of plane behaviour of these walls is rather difficult, due to the presence of large deformable roof structures and to the slenderness limits imposed to overcome problems with instability.

For this system, a 'C' shaped unit to be used very simply with the possibility of putting it in place after the vertical reinforcement has been already placed, and with dimensions that allow it to be used in two different directions (but still with vertical holes) will be developed (see Figure 4(b)). Again, the properties of the perforated clay unit are to be designed and studied, in particular for what affects the shape (geometry of the unit) in order to allow the creation of all the needed structural details and also allows the proper filling of the mortar that surrounds the reinforcement and to consider the use of specific blocks for concentrated nuclei. In this case the development of the mechanical properties of the unit is less important (but still necessary) as units with vertical holes generally meet the main required structural performance. The properties of the mortar are particularly important to give a consistency that allows a proper vertical filling where the reinforcement is placed (this could be also done with concrete, but the use of a fluid mortar would allow the use of a single material for the entire masonry element). The possibility of using lightweight mortar to preserve good thermal properties is of basic importance. Another property that can be improved with the use of this system is the bond between mortar and unit by placing staggered units. The reinforcement can be made with normal steel bars. Uncoupling of the reinforcement will be possible through the hole in the 'C' shaped unit, and special reinforcement types have been developed to improve the out-of-plane properties.

In this case, the main issue of the testing program is to check the two possible structural configurations for the out-of-plane behaviour of the reinforced masonry walls. One consists in buildings made with deformable roofs in which the walls can be tentatively considered as cantilevers with a vertical load applied at the top and a horizontal load due to the masses of both the roof and the wall itself. If the roof is stiff, than the horizontal action can be mainly distributed to the in-plane loaded walls. The out-of-plane walls, in the case of seismic action, are mainly loaded by the forces generated by their own mass and where the roof can be considered a very stiff elastic restraint and acting only for its dead-load. Two types of tests will be thus carried out: for the first configuration, a real scale structure will be built and tested by applying a horizontal load to the horizontal slab (see Figure 5(a)). For the second structural configuration, considering that the behaviour is more similar to the usual flexural behaviour (generally tested as in Figure 5(b) [13]), flexural tests on pre-stressed specimens will be carried out.

4. CONSTRUCTION SYSTEM BASED ON THE USE OF CONCRETE UNITS

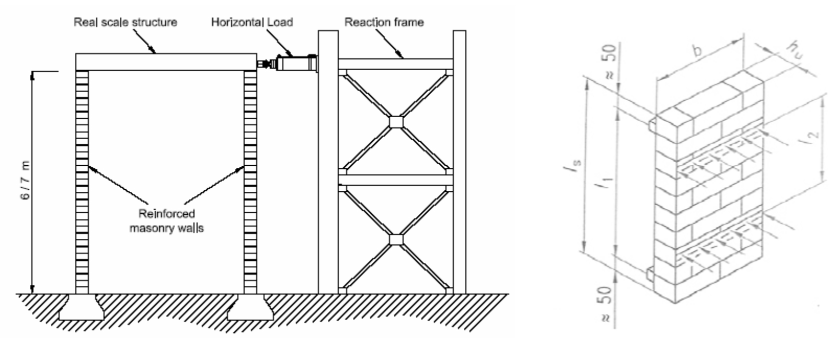
4.1 Introduction

In Portugal, the typical modern residential buildings are mainly constructed in reinforced concrete, steel being preferred for industrial buildings. Masonry has been used almost exclusively as infill material for the reinforced concrete frames. Only recently, a few horizontally reinforced non-load bearing walls are known to have been used on public buildings. Therefore, the major challenge that has to be faced in the Portuguese construction industry is the development of an effective and attractive load bearing masonry construction system that is able to convince contractors to use it in standard structures. This means that new masonry concrete units need to be developed to form the basis of a new load bearing system. The solutions to be studied aim to cover both load bearing and non-load bearing walls without introducing considerable changes to the traditional construction techniques.

4.2 Systems to withstand seismic loading

Portugal is a country with very different seismic risk zones with low to high seismic risks. Thus, within the scope of the DISWall project, two distinct construction systems are proposed for reinforced masonry walls to be used in general masonry buildings located in zones with moderate to high seismic hazards. Both construction systems are based on concrete masonry units the geometry and mechanical properties of which have to be specially designed to be used for structural purposes. It is foreseen that two and three cell hollow concrete masonry units will be developed in order to allow vertical reinforcement to be properly accommodated. The concrete masonry block with two vertical hollow cells is quite similar to the typical blocks used for non-load bearing walls. The concrete block with three hollow cells will be especially formulated to accommodate uniformly spaced vertical reinforcement. It should be noted that the easy acceptance of the proposed novel construction systems by the contractors requires that minimal changes to the traditional working practices are needed.

The first construction system CS1 is composed of two hollow cell concrete masonry units where the vertical reinforcements are placed in a continuous vertical joint, by adopting the masonry bond indicated in Figure 6(a), and with the horizontal reinforcements placed in the bed joints. Prefabricated truss type reinforcements (Murfor RND Z) will be used for the vertical and horizontal mortar joints. This construction system enables the easy placing of the units in the wall after the positioning of the continuous vertical reinforcement. This is in complete agreement with the traditional techniques commonly used for the construction of unreinforced masonry walls. An important aspect to be taken into account during the construction is the appropriate filling of the vertical reinforced joints so that suitable bond strength between reinforcement and masonry can be achieved thus providing an effective stress transfer mechanism between the two materials. An alternative to this construction system consists of placing the vertical reinforcements inside the hollow cells. If on one hand this can make the filling of the hollow cell easier, on the other hand it implies that an overlapping of the vertical reinforcement must be made to keep the rules of traditional workmanship. Apart from the mechanical requirements of the blocks to be used for structural purposes, this construction system can be reasonably adopted by the Portuguese contactors since it uses well know masonry units and no additional changes to the constructive process are needed.



(a) (b)

Figure 5 Out-of-plane tests procedures: (a) preliminary scheme of testing on the real scale walls; (b) standardized flexural test according to the EN 1052-2 [13].

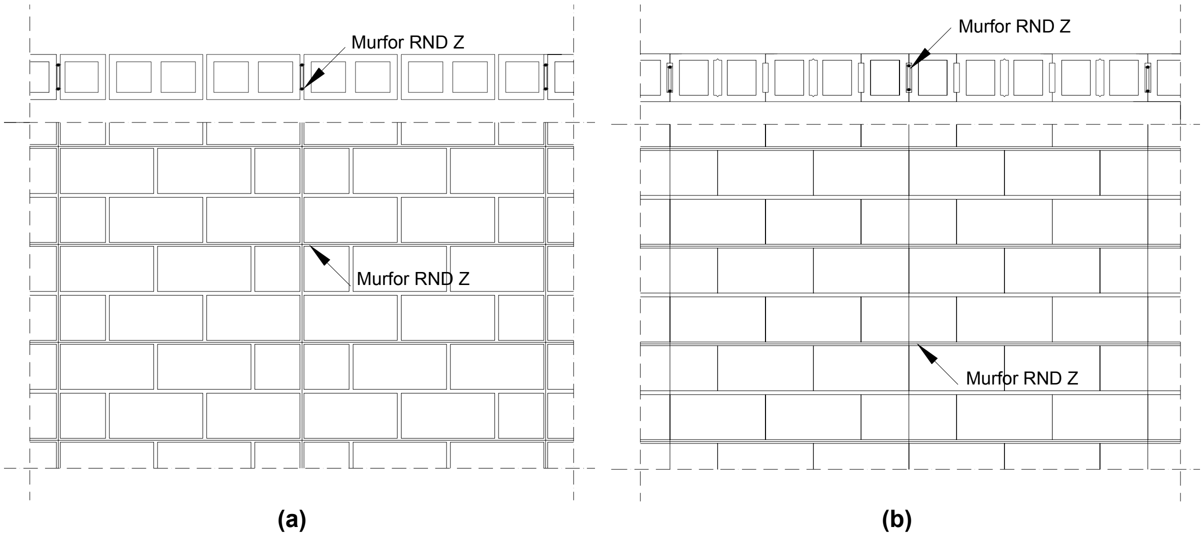


Figure 6 Construction systems based on the use of concrete units; (a) two hollow cell concrete units; (b) three hollow cell concrete units

The second construction system CS2 uses the three hollow cell concrete units, see Figure 6(b). If the traditional masonry bond is used, the vertical reinforcement (Murfor RND Z) can be introduced both in the internal hollow cell and in the hollow cell formed by the recessed ends. In this case, both continuous and overlapped vertical reinforcements are possible. If the masonry bond indicated in Figure 6(b) is adopted, the masonry units can be placed after the continuous vertical reinforcement has been positioned. An important issue to be taken into account in this construction system concerns the proper filling of the vertical hollow cells, since it is intended to substitute the usual grout by the general purpose mortar used for the bed joints in order to simplify the construction process. This leads to the need to design a mortar with adequate workability and flow properties. This construction system will also use Murfor RND Z bed joint reinforcement. With respect to both construction systems, anchorage systems to fix the vertical reinforcement to the slabs alternative to the traditional anchorages will be proposed.

The performance of each construction system when subjected to seismic forces will be evaluated by means of an extensive experimental program. The in-plane cyclic behaviour of the walls will be analysed from the results of in-plane deformation controlled static cyclic tests to be carried out on small cantilever masonry panels submitted to a pre-compression level. The out-of-plane behaviour will be studied from monotonic four-point bending tests. The influence of the in-plane damage on the out-of-plane performance of masonry walls will be analysed by means of combined tests. The influence of both vertical and horizontal reinforcement will be assessed by varying its percentage and distribution on the walls. The analysis of the contribution of the reinforcements to the global response of the masonry walls as well as the evaluation of the bond strength will be carried out through a careful monitoring of their deformation by means of strain gauges. The proposed test set-up to carry out the experimental tests can be seen in Figure 7.

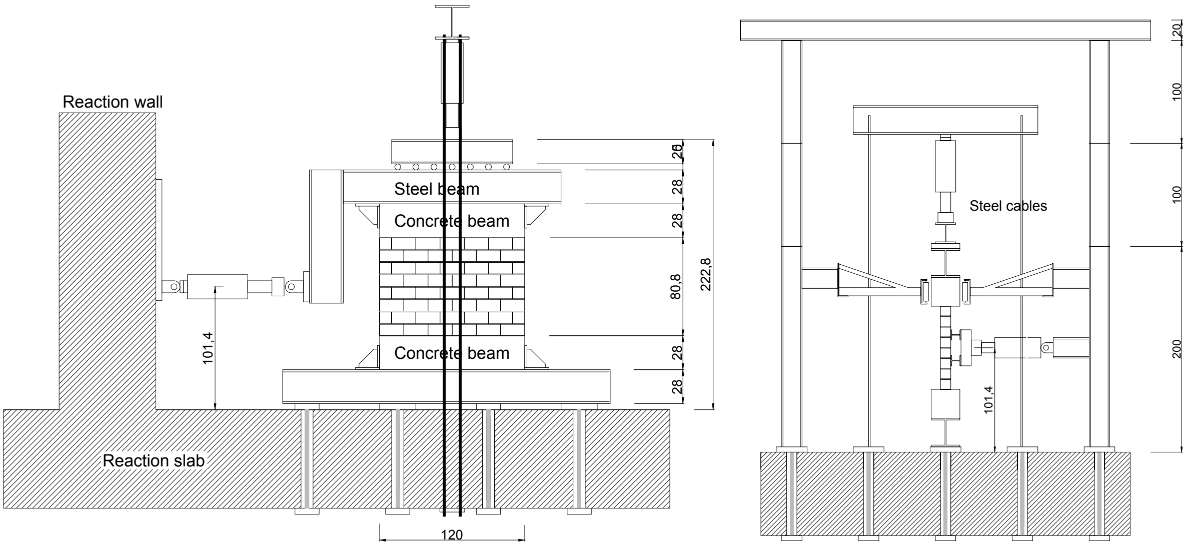
5. CONSTRUCTION SYSTEM BASED ON THE USE OF LARGE HOLLOW CLAY UNITS

5.1 Introduction

In Germany, due to the increased design requirements, it is necessary to develop masonry with an increased load bearing capacity or to fully exploit the existing load bearing capacities by the adoption of new design procedures. An appropriate approach for this purpose is the use of filled hollow clay masonry units. These hollow clay units (see Figure 8) have large holes which are filled with mortar or flowable concrete. Inside these holes vertical reinforcement can be installed. Furthermore it is possible to arrange horizontal reinforcement by introducing recesses in the cross web of the hollow clay units. The application and the design of these units are regulated by general inspection approvals so far. These approvals allow the application of either the load bearing capacity of the unfilled hollow clay units or the load bearing capacity of the concrete. A structural design considering the total load bearing behaviour of the bonded materials is not possible so far.

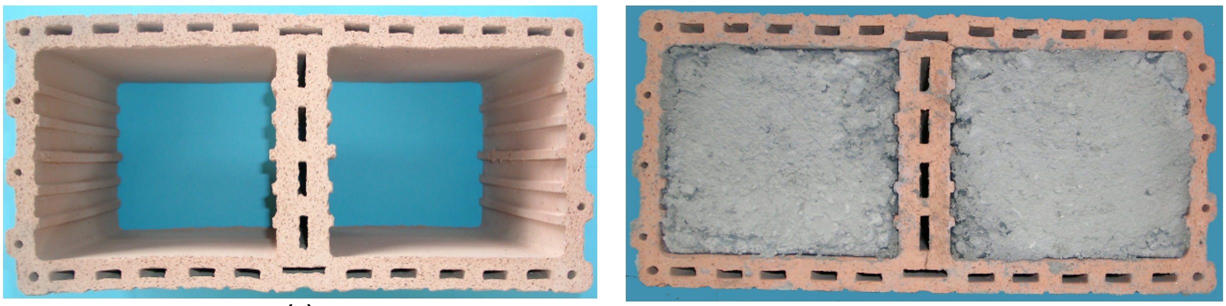
5.2 System with large hollow clay units and self-compacting concrete

Within the research project DISWall, this building method will be optimized and existing load bearing capacities will be utilized by taking the bond between the units and the concrete into account. For this, first of all the properties of the masonry components, hollow clay units and concrete, will be improved considering for example the substantial properties from the point of view of the structural designer and the producer. As regards the hollow clay units, it is important to adapt, among the other things, the geometrical and mechanical properties. This adaptation will be supported using the Finite-Element-Method. The general mechanical material parameters of each component of the composite construction method with large hollow clay units needed for the Finite-Element-Simulations will be determined by means of practical tests on small specimens (for example, fracture mechanical properties of the concrete and the unit material).



(a) (b)

Figure 7 Test setup; (a) Front view; (b) side view



(a) (b)

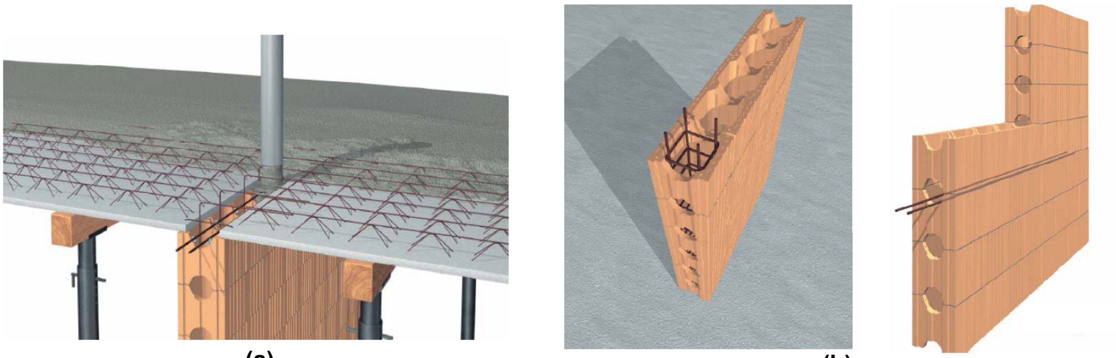
Figure 8 Large hollow clay units: (a) unfilled; (b) filled with vibrated concrete

To fill the holes of the hollow clay units a self-compacting concrete will be developed. On one hand filling the hollow clay units will be made easier and the probability of voids in the concrete infill will be reduced. On the other hand, the concrete properties will be adapted to the formulated requirements. The flow properties of the fresh concrete will be adjusted using special tests such as the L-Box-tests [14] which will be modified specifically for this research.

In addition, special reinforcement elements to improve the seismic capacity of the masonry walls made of hollow clay units will be designed. The aim within the development process is to achieve an easily installed and economic system of reinforcement for both the horizontal and vertical directions for which the correct positioning inside the units can be ensured and which can be handled simply. Furthermore it should be possible to anchor the reinforcement on the top and bottom slab if it is necessary.

Figure 9 shows a view of the system currently used, which will be studied and improved during the research.

For the optimized building materials, a calculation approach will be compiled which allows the load bearing behaviour of the bonded materials (hollow clay units, concrete and reinforcement) to be considered. In addition, the purpose of the new approach is to utilize the existing reserves of the bearing capacity of the structure. Several tests are planned to be carried out to characterize and adjust the critical parameters of the masonry walls made out of the optimized materials. Shear and compression tests on masonry panels under static-cyclic and static loading respectively are used to investigate the influence of different parameters. After that, the tests will be simulated in numerical models using the Finite-Element-Method. Afterwards, to develop a simple calculation approach for design rules, the numerical model will be reduced to the critical mechanical properties.



(a) (b)

Figure 9 System with large hollow clay units used so far: (a) general view; (b) details of vertical and horizontal reinforcement

6. CONCLUSIONS

In the present paper, the main objectives of a recently funded Co-operative Research Project, aimed at developing innovative systems for load and non-load-bearing reinforced masonry buildings, are presented. The different reinforced masonry systems that are being studied and developed by the partners, which cover most of the masonry construction tradition of the different European countries, are described and the main issues related to the experimental testing of these systems are presented. Analytical studies will follow the testing phase, in order to characterize fully the envisaged masonry systems. At the current stage, the experimental tests have just started and are going to be carried out during the next few months.

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