MID1.0: Masonry Infilled RC Frame Experimental Database

F. De Luca[1(✉)], E. Morciano[1,2], D. Perrone[2,3], and M. A. Aiello[2]

[1] Department of Civil Engineering, University of Bristol, Bristol, UK
flavia.deluca@bristol.ac.uk
[2] Department of Engineering for Innovation, University of Salento, Lecce, Italy
[3] Scuola Universitaria Superiore IUSS di Pavia, Pavia, Italy

Abstract. Experimental campaigns are a key tool for the evaluation of the behaviour of Masonry Infilled Reinforced Concrete (RC) frames. The case of masonry infills in RC frames is also a regional feature making the homogenous classification for a database a real challenge. This first attempt of a Masonry Infill Database (MID) includes a preliminary selection of experimental tests carried out on models of masonry-infilled RC frames under quasi-static or pseudo-dynamic loading. Each test is characterized in order to include, in a homogenous framework, all the relevant aspects of different experimental campaigns for easy access to the data for future applications. A Damage Classification is introduced, valid for both solid infill panels and for infill with openings. Finally, all monotonic backbones are fitted with a force-displacement piecewise linear approximation for future applications in Performance Based Earthquake Engineering.

Keywords: Reinforced Concrete · Masonry infills · Experimental Test Database

1 Introduction

The role played by masonry infills in reinforced concrete (RC) structures has been the subject of several studies in the last decades. Infills' presence is very common in the design practice of many seismic prone regions, especially in Mediterranean countries, and in general in Europe. A proper understanding of their seismic behaviour is required in order to reduce the risk of human and economic losses associated with seismic collapses.

Many studies have pointed out how significant is the influence of infills on the seismic response of structures. If, on one hand, this contribution increases the stiffness and the strength of structures, on the other, it may lead to some undesired consequences, such as the activation of failure modes associated with the interaction between the infill and the RC frame.

The interaction of the infill panel with the frame at global and local level can result in flexural or shear failures of the boundary RC structure. The above failures have often been observed during in-field campaigns after earthquakes and they have also been strongly evident in static and dynamic experimental tests (e.g., Mehrabi et al. 1996, FEMA306 1998; Fardis et al. 1999).

M. di Prisco and M. Menegotto (Eds.): ICD 2016, LNCE 10, pp. 147–160, 2018.
https://doi.org/10.1007/978-3-319-78936-1_11

Infill distribution in plan and elevation on the structure must be taken into account against the potential formation of soft storey mechanisms. Examples of progressive soft storey collapses likely caused by local interaction with infills are provided in the literature (e.g., Verderame et al. 2011, Negro and Colombo 1997). Last, but not least, one of the most important aspects related to this structural typology is the difficulty in performing quality controls of the materials and especially of the manufacturing process.

At the present time, there are several analytical and numerical studies on the behaviour of masonry infilled RC frames. Nevertheless, their "composite" nature imposes the necessity of ever newer and more sophisticated models and more reliable techniques to define their characteristics. Despite recent advances in computational power, a finite element micro-model (FEM) approach can be too intensive, especially for seismic risk assessments demanding numerous simulations. Instead, the equivalent strut macro-models seem to be a convenient approach. These simplified models replace the single panel with an equivalent strut having stiffness and width proportional to the characteristics of masonry, and the same thickness. Numerous equations have been proposed for the evaluation of strength and stiffness of the strut, but there is limited consensus on which equation is the most reliable; this is due to the limited systematic experimental experience available (Chrysostomou and Asteris 2012).

The assessment of the seismic performance and vulnerability is affected by several uncertainties, associated with the nature of the infill masonry and their interaction with the RC frame. Therefore, experimental campaigns turn out to be a key tool for the evaluation of the behaviour of the structural complex and to study the interaction between the infill panel and the frame. Unfortunately, it is quite rare to have a single, homogeneous experimental campaign fulfilling the wide variety of infills that can be found in practice. As a result, first, it is important to collect the experimental efforts to have a broader quantitative and controlled picture of the effect provided by infills to the structural behaviour of RC frames. This is the main framework of this study.

Based on the recent experience gained in structural and earthquake engineering, the idea of putting together a proper and, to some extent, fulfilling, database of experimental results on infilled RC structures is the main challenge herein.

For instance, in recent codes it is possible to find empirical formulations for the modelling of flexural and shear behaviour of RC elements, based on experimental databases previously collected by scientists and progressively updated over the years (e.g., Panagiotakos and Fardis 2001; Berry et al. 2004; Biskinis and Fardis 2010a, 2010b; Biskinis et al. 2004).

An experimental database of masonry infilled RC frames is a challenge far beyond the other experiences available in literature made for only the RC members. In fact, in this case the experimental campaign can vary significantly in many aspects (e.g., scale of the specimen, number of storeys, openings, etc.). Additionally, it is fundamental to account for the variety and variability of masonry, concrete, reinforcements, and finally their relative properties. Attempts to collect and homogenize experimental campaigns available in literature have been made recently (Cardone and Perrone 2015; Sassun et al. 2016) aimed at the use in loss estimation problems. The key issue is that a slight change in the above characteristics can change the relative ratios between relevant variables such as strength or stiffness, ending up in a significantly different behaviour (and mode of failure) for the masonry infilled RC unit.

The results of experimental campaigns have been fundamental not only to enlarge the experimental knowledge, but also for the further processes of calibration and comparison of the proposed models and predictive strategies. After an extensive analysis of all the experimental data available in literature and of the most effective techniques of modelling used for masonry-infilled RC frames, the significant properties and characteristics were selected in terms of:

- Materials used for the campaign;
- Geometric characteristics of the specimens;
- Characteristics, setup and scope of the test;
- Results of the campaign.

As it can be recognized by a first overview of literature sources on experimental tests on this topic, unfortunately not all the experimental campaigns are carried out or, at least documented, with the same level of accuracy. Therefore, after a preliminary selection of a large list of experimental references on the topic, it was necessary, at this preliminary stage, to select those sources that were significant, described in detail, and providing high quality data. In most cases, the refinement of the selection has ended up in the selection of recent studies (high quality of photos and artworks), even if some literature "milestones" are kept and considered first given their historical relevance and also given the significance they had for further experimental tests set up (e.g., Mehrabi et al. 1994).

The above approach was the best one for the selection of the proper entries for the database. Following up this preliminary step, it will be possible to include progressively all the references not included in this first step.

Four main objectives have been considered in this first version: (i) to include in the database a significant (in terms of number and variety) selection of the experimental tests carried out on scale models of masonry-infilled RC frames under quasi-static or pseudo-dynamic loading; (ii) to characterize each test in order to include all the significant aspects of each campaign for easy access to the data for future applications; (iii) to introduce a "Damage Classification" based on previous classifications and based on the analysis of the collected data, valid for both solid infill panels and for infill panels with openings; (iv) to model a force-displacement capacity backbone for the RC +masonry infill complex through the piecewise linear approximation by De Luca et al. (2013), aimed at different large scale and detailed earthquake and structural engineering applications. Even if the piece-wise linear fit cannot be of immediate use for calibration of infills analytical models, it can provide relevant results for large-scale approaches in which the full backbone of the complex RC+masonry infill is of interest.

Furthermore, the way the characteristics of each test are influencing the piece-wise linear fit can still provide useful insights for infill macro modelling efforts.

2 The Database

The Masonry Infill Database, in its current version, (MID1.0) includes the results of 16 experimental campaigns, collecting the results of 114 tests, in which 13 are bare tests (included for benchmarking purposes) and 101 are tests of masonry infills.

In Table 1, the campaign identification number (ID), the principal references, and the additional sources of information are listed for each experimental campaign included in the database. In many cases, in fact, it was necessary to retrieve complete information from other sources with respect to the principal one. Each test has a numerical ID based on the ID of the campaign and a progressive numbering for the specimen (e.g., 3_3, is the third specimen of the campaign by Mehrabi).

Table 1. References' list of the 16 experimental campaigns considered in MID1.0

ID	Reference	Additional sources
1	Kakaletsis and Karayannis (2009)	Kakaletsis and Karayannis (2008)
2	Haris and Hortobágyi (2015)	–
3	Mehrabi et al. (1994)	Mehrabi et al. (1996)
4	Crisafulli (1997)	Crisafulli et al. (2005)
5	Colangelo (2003)	Biondi et al. (2000) Colangelo (2005)
6	Colangelo (1996)	Biondi et al. (2000) Colangelo (2005)
7	Colangelo (2004)	Biondi et al. (2000) Colangelo (2005)
8	Al-Chaar et al. (2002)	–
9	Baran and Sevil (2010)	–
10	Calvi and Bolognini (2001)	Calvi et al. (2004)
11	Al-Nimry (2014)	–
12	Cavalier and Di Trapani (2014)	–
13	Basha and Kaushik (2012)	Basha and Kaushik (2016)
14	Zovkić et al. (2012)	Zovkic et al. (2013)
15	Pires and Carvalho (1992)	Skafida et al. (2014)
16	Kyriakides (2001)	Skafida et al. (2014)

The database has been collected in a Microsoft Excel© Spreadsheet with six separate sections. Section 1, SPECIMEN - summarizes specimen characteristics in terms of typologies of the tests, number of storeys, bays, test scale, type of vertical and horizontal loading applied, geometrical information about the presence of openings in the infill panel. Section 1 has 17 different entries. In Figs. 1, 2 and 3 the different distributions referred to the 113 specimens considered are provided for most relevant parameters of this section. Section 2, PANEL - summarizes all the characteristics of the infill panel and it has 23 entries including the characteristics of the masonry block, of the mortar and the masonry prism. Some entries in this section are often empty or not available (n.a.). In fact, the way the masonry infill is characterized geometrically and mechanically is really campaign-dependent and the high number of entries in this section allows MID1.0 being adaptable to the different choices that authors made.

Figures 4, 5 and 6 shows the distributions of some of the properties in Sect. 2 of the database. In this case the total number of specimens considered is 101, discarding the

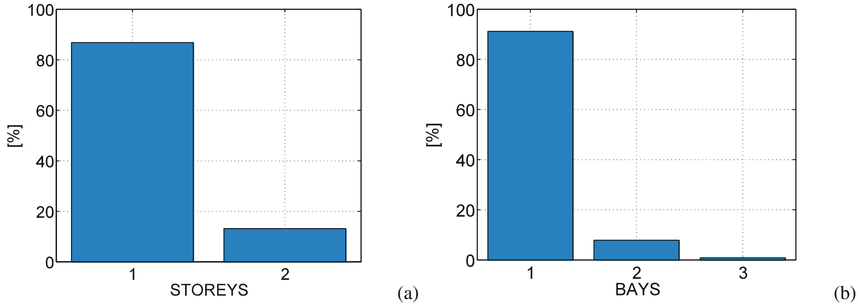


Fig. 1. (a) Number of storeys and (b) number of bays in MID1.0

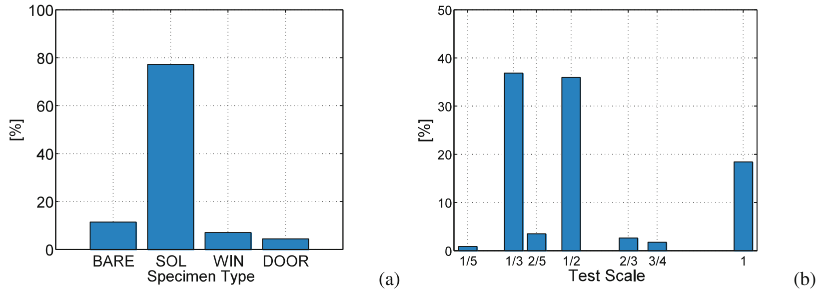


Fig. 2. (a) Specimen type BARE: bare, SOL: solid, WIN: window, DOOR: door (including information on the size of the opening), (b) test scale in MID1.0.

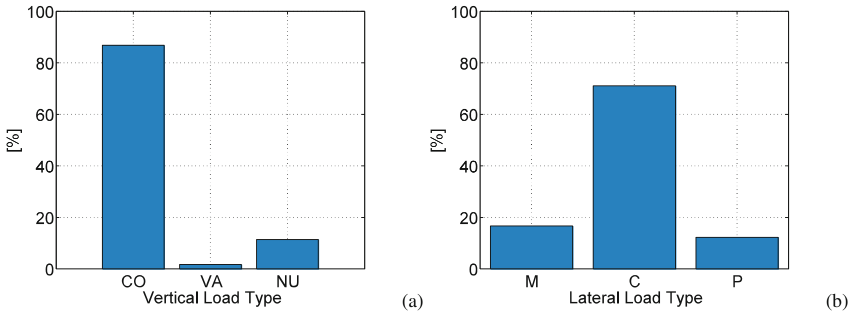


Fig. 3. (a) Vertical load type CO: constant, VA: variable, NU: null and (b) lateral load type M: monotonic, C: cylic (pseudo-static), and P(pseudo-dynamic) in MID1.0

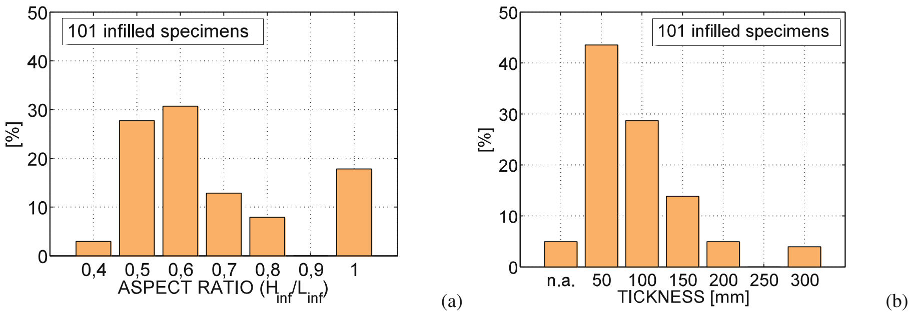


Fig. 4. (a) Aspect ratio, and (b) thickness of the infill panel in MID1.0

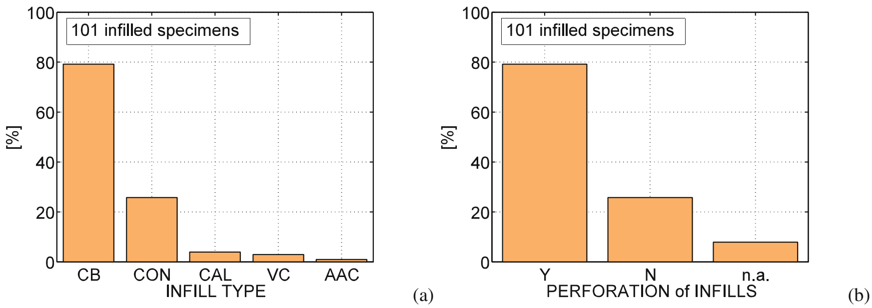


Fig. 5. (a) Infill type CB: clay bricks, CON: concrete, CAL: calcarenite, VC: vetro-ceramic, AAC: autoclaved aerated concrete, and (b) perforation of the infills Y: yes, N: no, n.a.: not available in MID1.0

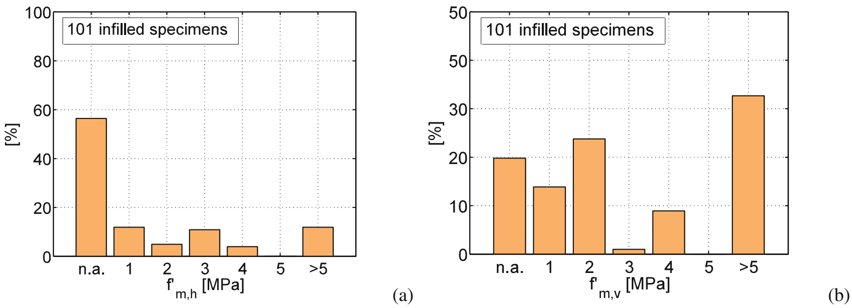


Fig. 6. (a) Horizontal and (b) vertical compressive strength of for the masonry infill prisms in MID1.0.

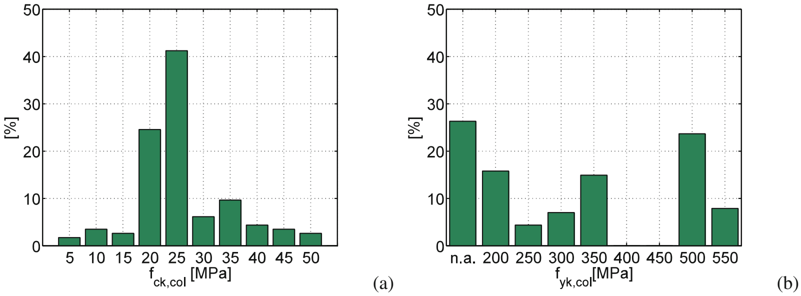


Fig. 7. (a) Concrete compressive strength ($f_{ck,col}$), and (b) steel yielding strength ($f_{yk,col}$) for RC columns in MID1.0

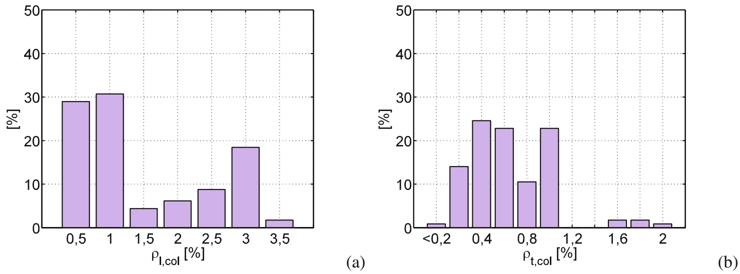


Fig. 8. (a) Longitudinal ($\rho_{l,col}$) and (b) transversal ($\rho_{t,col}$) reinforcement ratio of columns in MID1.0.

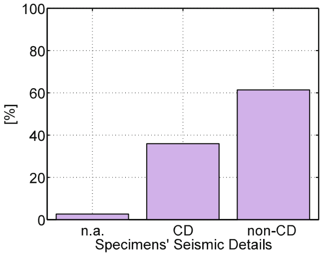


Fig. 9. Seismic detailing of the specimens CD: capacity-designed, non-CD: no capacity design, n.a.: not available in MID1.0.

13 bare tests included. Section 3, FRAME - summarizes all the characteristics of the reinforced concrete frame, including dimensions of columns, beams, base beam, and mechanical properties of concrete and reinforcement steel. This section has 25 entries. Figure 7 shows the distributions of two entries of this section; the compressive strength of concrete and yielding strength of steel in the columns.

Section 4, REINFORCEMENT - summarizes all the characteristics of longitudinal and transversal steel reinforcements in columns and beams of the RC frames. This section has 26 data entries. Columns' and beams' sections have been grouped in typologies in analogy to the approach employed in Berry et al. (2004). Figure 8 shows the geometric percentage of longitudinal and transversal reinforcement in columns. Figure 9 provides information on seismic detailing of the specimens. In this context "seismic detailing" should be interpreted as "capacity-designed"; i.e., conforming to general capacity design rules of modern codes.

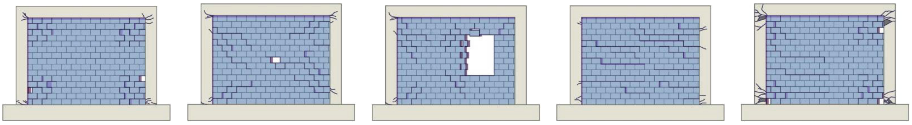
2.1 Damage Classification and Failure Modes

Section 5, FAILURE MODE - includes information concerning the behaviour of the specimens to lateral loading and at collapse, it is referred only to the 101 infilled specimens. This section includes drifts at two different damage states (DS2 and DS3) and a novel classification of failure modes (it has three entries). This is an output section of the database; in fact, in many cases it was necessary to provide an interpretation of damage descriptions or, where possible, to carry out drift values from the force displacement behavior of the specimen.

The classification of failure modes for masonry infilled frames has been done in different studies such as Mehrabi et al. (1994), Asteris et al. (2011). In particular, specific attention was given to failure modes related to solid masonry infills, while only a few studies tried to classify the behaviour of masonry infilled frames with openings such as Kakaletsis and Karayannis (2008) or FEMA306 (1998). In order to generate a unique general arrangement, useful to characterize the behaviour of both solid infill specimens and those with openings, a novel failure mode classification is introduced in MID1.0. The classification is shown in Table 2 and visual representation of each failure mode is schematically shown in Fig. 10.

Table 2. Failure mode classification in MID1.0

ID	Failure mode	Component involved	Solid infill	Partial infilled
A	Corner crushing	Masonry panel	√	√
B	Diagonal cracking	Masonry panel	√	-
C	Sub-panel diagonal cracking	Masonry panel	-	√
D	Bed joints sliding	Masonry panel	√	√
E	RC frame failure	RC frame	√	√



(a) (b) (c) (d) (e)

Fig. 10. Failure mode classification (a) corner crushing, (b) diagonal cracking, (c) sub-panel diagonal cracking, (d) bed joints sliding, (e) RC frame failure as classified in MID1.0

For each failure mode, a description is provided similarly to the approach of FEMA306 (1998). Description of *corner crushing* (A) is "complete loss of resistance of the blocks in the corners through spalling of face shells and diagonal cracking in the adjacent area. The damage can be spread into the whole panel but is more evident in the corners. This may lead to imminent formation of plastic hinges in the RC frame". *Diagonal cracking* (B) is "numerous diagonal cracks ranging from corner to corner of the infill panel, in both directions. Usually associated with slight crush of corners and/or with expulsion of blocks from the middle area of the panel". Description of *Sub-panel Diagonal Cracking* (C) is "numerous diagonal cracks ranging from corner to corner of the sub-panel, usually from the edge of the opening to the corners. Usually associated with loss of stability of the opening, slight crush of corners in the sub-panel and/or with expulsion of blocks from the middle area".

Description of *bed joint sliding* (D) is "the main cracking pattern in the middle area of the infill is concentrated in a few (or a single) horizontal cracks in correspondence of bed joints, where the greatest displacement occurs. This failure mode could also happen through a more homogenous distribution of horizontal cracks". Finally, description of *RC frame failure* (E) is "the failure mode can happen by isolated collapse of a single element of the RC frame, typically related to a strength deficit, or after the formation of at least two out of the four previous failure modes. Almost uniform damage can be acknowledged in the infill, with complex cracking pattern, blocks spalling and large crushing".

In this first version of MID1.0, failure mode was defined only for the specimens in which the authors of the experimental campaigns were providing enough details to identify clearly the failure mode or in cases in which they were classifying the failure.

Failure mode classification is provided for 55 specimens only; Fig. 11 shows the distribution of failure modes excluding the cases in which this information was not available (i.e., 100% corresponds to 55 specimens). When the failure mode description of the specimen included characteristics of more than one failure mode and authors were mentioning more than one failure mode we considered hybrid categories (e.g., AB, AD, BE, CA, DA, DC, DE), in which the first letter identifies the dominant failure mode.

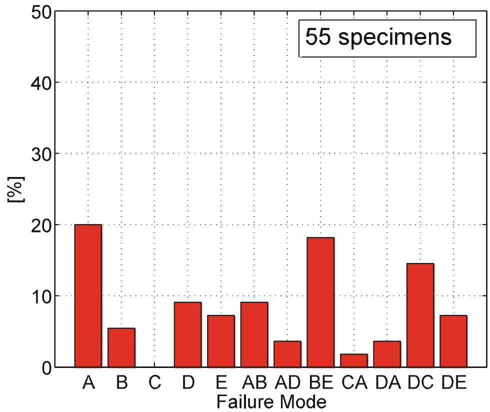


Fig. 11. Failure modes observed on 55 infilled specimens in MID1.0

Damage states (DS_i) were characterized and interpreted according to the EMS98 definition for damage to infills, see Grunthal et al. (1998) and De Luca et al. (2015) for further details. In particular, we defined as DS2, the so-called *moderate damage* (i.e., cracks in infill walls; fall of brittle cladding plaster; falling mortar from the joints of wall panels), and as DS3, the so-called *heavy damage* (i.e., large cracks in the infill wall). Damage state data were not available for all the specimens, DS2 was defined in 53 specimens, while DS3 was defined in 55 specimens over the total of 101 infilled specimens. In Figs. 12 and 13 are shown the distribution of DS2 and DS3 in MID1.0 over the total of specimens for which this information was provided.

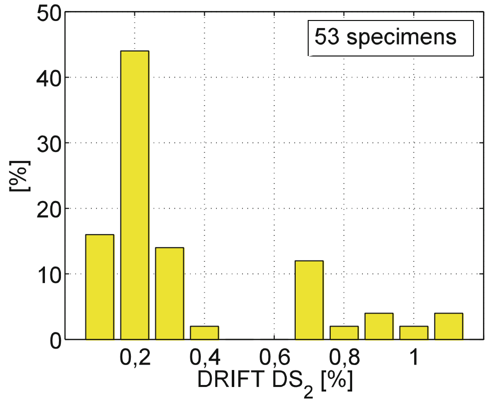


Fig. 12. DS2 drift of 53 infilled specimens in MID1.0

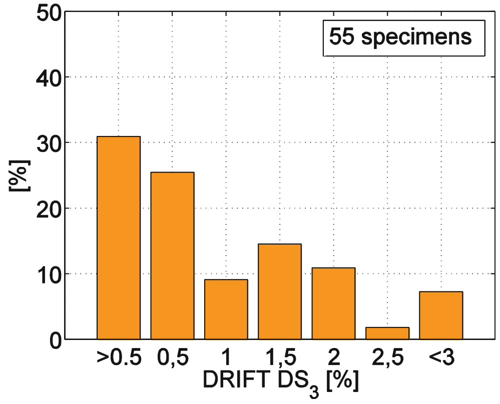


Fig. 13. DS3 drift of 55 infilled specimens in MID1

Section 6 of the database, PIECEWISE LINEAR MODEL includes the multi-linear fits of the monotonic envelope of each test included in the database. To do so, for each test, the monotonic envelope has been drawn. In the case of cyclic tests, positive and

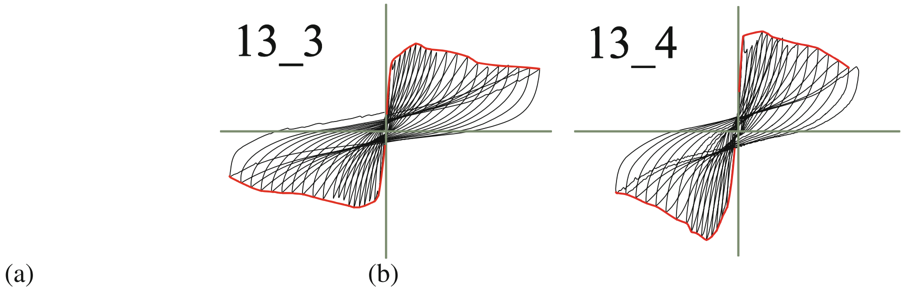


Fig. 14. Force-Displacement cyclic response of specimens 3 and 4 of campaign 13 (i.e., 13_3 and 13_4) and monotonic envelope produced in MID1.0 (adapted from Basha and Kaushik 2012 and 2016)

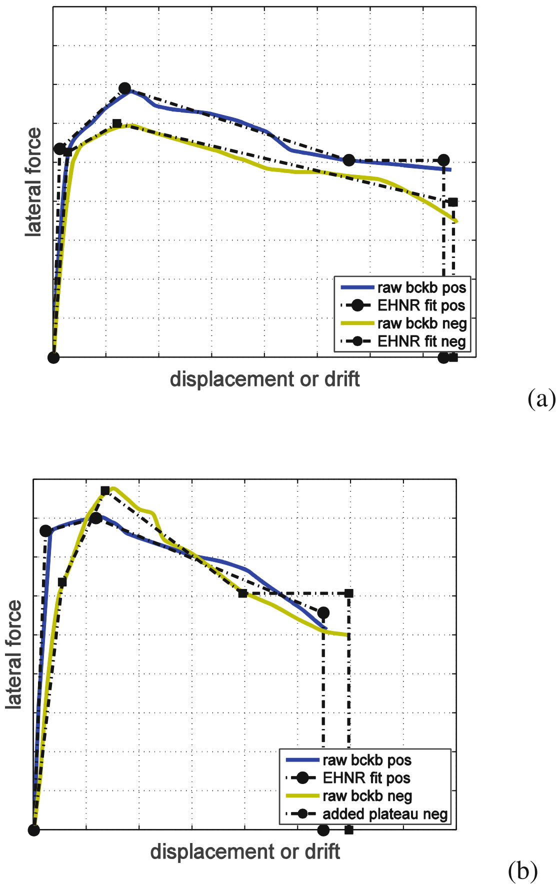


Fig. 15. Piecewise multi-linear fit of tests (a) 13_3 and (b) 13_4 in MID1.0

negative envelopes are considered. An example of the envelopes is shown in Fig. 14. This section of the database includes the coordinates of the five points of the fit for each monotonic branch of the test made according to the optimized algorithm by De Luca et al. (2013). All the 114 tests were fitted. For instance, Fig. 15 shows the multi-linear fits of positive and negative branches of the two tests in Fig. 14.

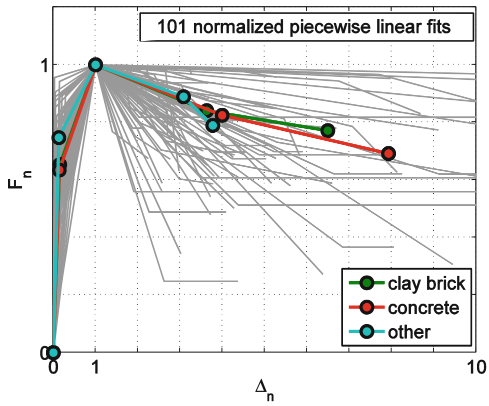


Fig. 16. Average normalized backbones per infill typology in MID1.0

The fits of the 101 infilled test (averaging positive and negative fits when both were available) were put together to have a preliminary normalized backbone shape for the test included in MID1.0. Figure 16 shows the average normalized shapes in MID1.0 for different infill typologies (i.e., clay brick, concrete, other) as classified in Fig. 5a.

3 Conclusions

MID1.0 is the first attempt of database of experimental tests on masonry infilled RC frames. It includes 101 test data. In this preliminary version, the database provides damage data, a failure mode classification and a normalized fit of all the tests for future analytical applications.

References

Al-Chaar G, Issa M, Sweeney S (2002) Behavior of masonry-infilled nonductile reinforced concrete frames. J Struct Eng 128(8):1055–1063

Al-Nimry HS (2014) Quasi-static testing of RC infilled frames and confined stone-concrete bearing walls. J Earthq Eng 18(1):1–23

Asteris PG, Kakaletsis DJ, Chrysostomou CZ, Smyrou EE (2011) Failure modes of in-filled frames. Electr J Struct Eng 11(1):11–20

Baran M, Sevil T (2010) Analytical and experimental studies on infilled RC frames. Int J Phys Sci 5(13):1981–1998

Basha SH, Kaushik HB (2012) Evaluation of shear demand on columns of masonry infileld reinforced concrete frames. In: Proceedings of the 15th world conference on earthquake engineering, Lisbon, Portugal, 24–28 September 2012

Basha SH, Kaushik HB (2016) Behavior and failure mechanisms of masonry-infilled RC frames (in low-rise buildings) subject to lateral loading. Eng Struct 111:233–245

Berry M, Parrish M, Eberhard M (2004) PEER structural performance database user's manual (version 1.0). University of California, Berkeley

Biondi S, Colangelo F, Nuti C (2000) La risposta sismica dei telai con tamponature murarie. CNR Gruppo Nazionale per la Difesa dai Terremoti (in Italian)

Biskinis DE, Roupakias GK, Fardis, MN (2004) Degradation of shear strength of reinforced concrete members with inelastic cyclic displacements. ACI Struct J, 101(6):773–783

Biskinis D, Fardis MN (2010a) Deformations at flexural yielding of members with continuous or lap-spliced bars. Struct Concr 11(3):127–138

Biskinis D, Fardis MN (2010b) Flexure-controlled ultimate deformations of members with continuous or lap-spliced bars. Struct Concr 11(2):93–108

Calvi GM, Bolognini D (2001) Seismic response of reinforced concrete frames infilled with weakly reinforced masonry panels. J Earthq Eng 5(02):153–185

Calvi GM, Bolognini D, Penna A (2004) Seismic performance of masonry-infilled RC frames: benefits of slight reinforcements. Invited lecture to sesto congresso nacional de sismologia e engenharia sismica, pp 254–276

Cardone D, Perrone G (2015) Developing fragility curves and loss functions for masonry infill walls. Earthq Struct 9(1):257–279

Cavaleri L, Di Trapani F (2014) Cyclic response of masonry infilled RC frames: experimental results and simplified modeling. Soil Dyn Earthq Eng 65:224–242

Chrysostomou CZ, Asteris PG (2012) On the in-plane properties and capacities of infilled frames. Eng Struct 41:385–402

Crisafulli FJ (1997) Seismic behaviour of reinforced concrete structures with masonry infills, Ph. D. thesis, Department of Civil Engineering, University of Canterbury, 404 p

Crisafulli FJ, Carr AJ, Park R (2005) Experimental response of framed masonry structures designed with new reinforcing details. Bull N Z Soc Earthq Eng 38(1):19–32

Colangelo F (1996) Pseudo-dynamic seismic response of infilled RC frames designed for gravity loading. In: Proceedings of the 11th world conference on earthquake engineering, Acapulco, Mexico, 23–28 June 1996

Colangelo F (2003) Experimental evaluation of member-by-member models and damage indices for infilled frames. J Earthq Eng 7(01):25–50

Colangelo F (2004) Pseudo-dynamic seismic response of infilled RC frames designed for gravity loading. In: Proceedings of the 13th world conference on earthquake engineering, Vancouver, British Columbia, Canada, 1–6 August 2004

Colangelo F (2005) Pseudo-dynamic seismic response of reinforced concrete frames infilled with non-structural brick masonry. Earthq Eng Struct Dyn 34(10):1219–1241

De Luca F, Vamvatsikos D, Iervolino I (2013) Near-optimal piecewise linear fits of static pushover capacity curves for equivalent SDOF analysis. Earthq Eng Struct Dyn 42(4):523–543

De Luca F, Verderame GM, Manfredi G (2015) Analytical versus observational fragilities: the case of Pettino (L'Aquila) damage data database. Bull Earthq Eng 13(4):1161–1181

Fardis MN, Bousias SN, Franchioni G, Panagiotakos TB (1999) Seismic response and design of RC structures with plan-eccentric masonry infills. Earthq Eng Struct Dyn 28(2):173–191

FEMA 306 (1998) Evaluation of earthquake damaged concrete and masonry wall buildings (FEMA 306). Applied Technology Council, Redwood City

Grüntal G (1998) European macroseismic scale EMS-98. European Seismological Commission, Sub-commission on Engineering Seismology, Working Group Macroseismic Scales, Luxembourg

Haris I, Hortobágyi Z (2015) Comparison of experimental and analytical results on masonry infilled RC frames for cyclic lateral load. Period Polytech Civil Eng 59(2):193

Kakaletsis DJ, Karayannis CG (2008) Influence of masonry strength and openings on infilled R/C frames under cycling loading. J Earthq Eng 12(2):197–221

Kakaletsis DJ, Karayannis CG (2009) Experimental investigation of infilled reinforced concrete frames with openings. ACI Struct J 106(2):132

Kyriakides MA (2001) Seismic retrofit of unreinforced masonry infills in non-ductile reinforec concrete frames using engineered cementitious composites. Dissertation, Department of Civil and Enviromental Engineering, Stanford University, Stanford

Mehrabi AB, Shing PB, Schuller MP, Noland JL (1994) Performance of masonry-infilled R/C frames under in-plane lateral loads. Rep. CU/SR-94, p 6

Mehrabi AB, Benson Shing P, Schuller MP, Noland JL (1996) Experimental evaluation of masory-infilled RC frames. J Struct Eng 122(3):228–237

Negro P, Colombo A (1997) Irregularities induced by nonstructural masonry panels in framed buildings. Eng Struct 19(7):576–585

Panagiotakos TB, Fardis MN (2001) Deformations of reinforced concrete members at yielding and ultimate. Struct J 98(2):135–148

Pires F, Carvalho EC (1992) The behaviour of infilled reinforced concrete frames under horizontal cyclic loading. In: Proceedings of the 10th world conference on earthquake engineering, Madrid, Spain, 9–24 July 1992

Sassun K, Sullivan TJ, Morandi P, Cardone D (2016) Characterising the in-plane seismic performance of infill masonry. Bull N Z Soc Earthq Eng 49(1):100–117

Skafida S, Koutas L, Bousias SN (2014) Analytical modeling of masonry infilled RC frames and verification with experimental data. J Struct 2014:1–17

Verderame GM, De Luca F, Ricci P, Manfredi G (2011) Preliminary analysis of a soft-storey mechanism after the 2009 L'Aquila earthquake. Earthq Eng Struct Dyn 40:925–944

Zovkić J, Sigmund V, Guljaš I (2012) Testing of R/C frames with masonry infill of various strength. In: Proceedings of the 15th world conference on earthquake engineering, Lisbon, Portugal, 24–28 September 2012

Zovkic J, Sigmund V, Guljas I (2013) Cyclic testing of a single bay reinforced concrete frames with various types of masonry infill. Earthq Eng Struct Dyn 42(8):1131–1149