FRAGILITY FUNCTIONS FOR A DUTCH URM BUILDING TYPOLOGY INCLUDING FINITE-ELEMENT BASED COLLAPSE MODELLING

D. N. Grant[(1)], J. Dennis[(2)], R. Sturt[(3)], G. Milan[(2)], D. McLennan[(3)], P. Negrette[(2)], R. da Costa[(2)], M. Palmieri[(2)]

[(1)] *Advanced Digital Engineering, Arup UK, damian.grant@arup.com*
[(2)] *Arup Netherlands*
[(3)] *Advanced Digital Engineering, Arup UK*

Abstract

The development of seismic fragility functions for buildings generally relies on simplified modelling methods and the use of indirect engineering demand parameters for the determination of collapse. Through optimisation of the computational analysis cost, and the incorporation of statistically distributed model properties, this paper demonstrates the potential of non-linear finite element models including explicit progressive collapse prediction as a viable alternative. This paper presents an overview of the method developed and its application to unreinforced masonry (URM) terraced house buildings with cavity walls and concrete floors in the Groningen region of the Netherlands, where an understanding of the risk arising from induced seismicity is required. Multiple index buildings were selected to represent the variations in geometry, material properties, and connection types found within the typology. For each index building, Latin Hypercube sampling was used to generate batches of several hundred realisations of a finite element model (LS-DYNA time-history analysis), each selecting from a set of 100 hazard-consistent ground motions, and varying material properties and other uncertain variables according to pre-assigned probability distributions. Fragility functions were developed for the URM terraced house typology by combining results from the individual index buildings together.

Keywords: fragility functions, index buildings, unreinforced masonry, collapse modelling

1 Introduction

Probabilistic seismic risk assessment of distributed building stock – whether over a city, region, country or commercial property portfolio – typically involves grouping buildings into typologies. A typology is a grouping of building characteristics, which may include construction material, structural system, number of storeys, etc., with an underlying assumption that buildings with like characteristics will perform similarly in an earthquake. Each typology is assigned a fragility function, which give the probability of a building from the typology reaching a particular level of damage as a function of the intensity of seismic ground shaking.

Fragility functions can be developed on the basis of empirical data, analytical modelling or expert judgement [1]. Analytical methods are commonly used, and, if well-calibrated against real building performance or laboratory testing, can provide robust estimates of building damage and collapse probabilities. This is particularly useful for building typologies for which sufficient previous damage data is not available – e.g., tall buildings, for retrofitted buildings, or in cases of induced seismicity (NAM, 2019). The research literature is full of new analysis approaches, ways of processing analysis results, and applications of the methods to different structural types. Analytical approaches based on response history analysis are increasingly common; see [2] and [3] for some recent reviews of the current state of the art and outstanding challenges for the research community.

Most modelling methodologies have not been calibrated to model full collapse, and therefore it is common to introduce proxy engineering demand parameters (EDPs; e.g., interstorey drifts), and to assume that exceeding a threshold value of the EDP corresponds to reaching a particular damage state (e.g., collapse). Alternatively, collapse may be assumed when an analysis becomes unstable. Neither of these outcomes is a reliable indicator of the onset of collapse, since blanket EDPs may not consider the particular design features of the building, and numerical instability may indicate localised failure rather than global collapse. Nor do these outcomes allow the full consequences of collapse to be explored, in terms of what happens to the building after collapse is triggered, and what may be the risk to building occupants. This can be particularly important for typologies such as unreinforced masonry (URM) houses, where multiple failure modes can contribute to collapse response and different partial failure modes may be possible.

This paper describes using explicit finite element analysis for collapse fragility prediction for a URM building typology in the Groningen region in the Netherlands. This work was carried out to validate fragility functions calculated using more traditional (EDP-based) approaches for a probabilistic seismic risk assessment for induced seismicity in Groningen. Initial results on a single representative index building were reported in [4], and this paper extends the work by: (1) parametrically varying the properties of the index building model to cover a broader range of geometries and connection types; (2) carrying out fragility assessment on an additional four index buildings across the broad typology; and (3) combining results together to give a typology-wide fragility function.

2 Project Background

A seismic risk assessment is being carried out for induced seismicity in the Groningen region in the north of the Netherlands, to investigate the "local personal risk" for occupied buildings [5], [6]. The risk assessment comprises an exposure model for approximately 260,000 individual buildings in the area [7]. Buildings in the field are grouped into typologies, whereby buildings of a similar structural system are collected together on the grounds that their seismic behaviour should be comparable. To determine a fragility function for a typology, one or more representative index buildings from the typology are selected. In the original risk assessment, fragility functions were developed for each typology on the basis of a simplified modelling approach, calibrated on the results of deterministic finite element models of the index buildings subjected to suites of up to 11 ground motions. Modelling uncertainty and building-to-building variability were added later based on results from literature, judgement and comparison of blind predictions to test results [8].

At the time the work in this paper was being carried out, one building typology had been identified as particularly vulnerable: URM terraced house buildings with cavity walls, concrete floors and large window openings in the façade [5] (referred to as URM4L in the risk assessment). This typology was selected for further study using a direct detailed finite element approach. The fragility function for this typology had been developed based on an index building analysis model, representing an actual two-storey house located in the town of Loppersum. This index building is described as URM4L-1 in this paper. Detailed analysis results on this study building were carried out to develop collapse fragility functions, as previously reported in [4]; the methodology used and relevant results are summarised in the next section.

Fragility functions resulting from this assessment are applicable to this single study building only, and do not take into account the effect of building-to-building variability (including material properties, geometry, and connectivity between structural components) across the typology. To be confident of fully sampling this building-to-building variability would require analysing each of the ~40,000 real buildings that were assigned this typology, and, in each case, to also sample the epistemic uncertainty based on available material data and construction details of the buildings that may not be visible from a visual assessment. This is clearly not feasible (and would defeat the purpose of grouping buildings into typologies). Therefore, the approach adopted here was to decompose the building-to-building variability into: (1) variations in material properties, representative of variations for the whole typology, applied to a single index building (the study building described above); (2) variations in geometry, connectivity etc. found in a small pool of further index buildings. The distinction between these sources of variability is somewhat artificial (in reality, every building has its own geometry, connectivity and material properties), but taking this approach was found to be necessary to properly sample the typology.

Additional index buildings are described further in Section 6.1. They were selected from a wider pool of buildings that had been previously assessed by Arup as part of individual building assessment work that is currently taking place. Only two index buildings were available that strictly fell into the typology under consideration; these were therefore supplemented by three additional index buildings from a similar typology with the same structural system (URM terraced house with cavity walls and concrete floors), but with smaller openings in the façade. See Section 7 for the treatment of the results from the five index buildings.

3 Overview of Previous Work on URM4L-1 (First Index Building)

As noted in the last two sections, the first phase of work involved the development of fragility functions for a specific index building, URM4L-1. The methodology and results were described in [4]. Relevant information about this work is summarised in this section.

3.1 Modelling Approach

Analyses were carried out in LS-DYNA®, a versatile three-dimensional non-linear finite element analysis program used for seismic analysis among many other applications. LS-DYNA's explicit solver is particularly suited to large deformation analysis of brittle materials, where implicit time integration schemes may have difficulties with convergence. Unreinforced masonry (URM) components were modelled with a user material model (*MAT_SHELL_MASONRY), which allows a relatively coarse mesh of shell elements to represent the composite behaviour of bricks and mortar, and takes into account relevant failure modes in head joints, bed joints and bricks. Connections between components (such as nailed connections between timber elements and wall ties in cavity walls) are modelled explicitly with discrete elements with nonlinear force-displacement behaviour calibrated against experimental testing.

Progressive collapse, including the potential impact between falling elements and the floors beneath, and between different masonry walls, was modelled using LS-DYNA contact formulations. An algorithm was also developed to automatically track the accumulation of debris on floors and ground. Estimates of debris cover (area of floor plates impacted by debris normalised by the total floor area) were used to quantify the consequences of partial or full collapses, and this was linked to fatality rates in the risk assessment [8].

The material model, overall modelling approach and calibration with experimental testing are further described in [4] and [9].

3.2 Index Building Model Description

The study building model represents a two-storey, two-unit terraced house, with masonry cavity walls, concrete first floor one-way spanning onto end walls, timber attic floor and roof. Cavity walls are formed of calcium silicate (CaSi) inner leaf and clay brick outer leaf. See Fig. 1 for details of the study building and LS-DYNA modelling.

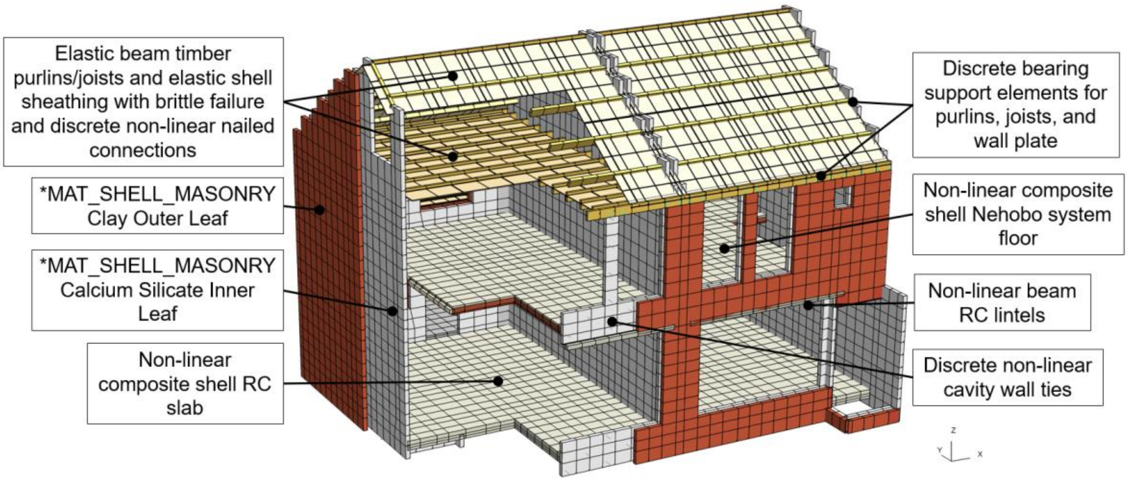


Fig. 1 – Original study index building model (URM4L-1) (corner of models hidden to show internal details)

The original study also included the effect of soil-structure interaction (SSI), including explicit modelling of the soil underneath the building, the piles supporting the building, and the interaction between piles and soil. Explicit modelling of soil-structure interaction was not found to have a significant effect on fragility results when compared to fixed base models [4]. SSI analyses on the original study building are therefore not covered further here, and the additional analyses covered in this paper were all conducted on fixed base models.

3.3 Treatment of Variability

Latin hypercube sampling (LHS) was used to generate 100s of combinations of building parameters and ground motions to include the effects of epistemic uncertainty and aleatoric variability in the fragility assessment. LHS generates random samples of parameter values for any number of random variables. Each random variable is assigned a probability distribution (which may be a continuous- or discrete-valued distribution), and each cumulative distribution function (CDF) is divided into a number of equiprobable bands equal to the number of analyses to be carried out. The combination of values for the variables is set up such that every band of the CDF is sampled exactly once (in the case of discrete variables, each value is sampled a number of times in proportion to its probability mass).

The number of simulations required does not depend on the number of variables. It was found that stable estimates of the fragility functions were obtained based on 300 LHS analyses.

In summary, the variables considered for the LHS were the following:

- *Ground motion inputs (record-to-record variability)*. A suite of 100 ground motions were selected to be compatible with the seismic hazard in Loppersum (Crowley, *pers. comm.*); 50 ground motions were selected based on a return period of 10,000 years and 50 based on a return period of 100,000 years. A conditional spectrum based approach was used [10], conditioned on the 0.5-second spectral acceleration. The specific ground motion used for each simulation is also treated as a discrete random variable; e.g., when 300 analyses are carried out, each of the 100 ground motions is used three times, along with variations of the other modelling parameters.
- *Masonry material properties*. Density, Young's modulus, Poisson's ratio, various strength metrics (compressive, tensile, shear, and diagonal tensile strength) and their associated fracture release

energies, and modelling parameters related to failure were included as continuous variables. Standard deviations for the properties were based on available laboratory and in situ test data on samples from the building itself or on buildings of a similar vintage. Mean properties for CaSi inner leaf and clay outer leaf were typically based on the Dutch seismic assessment code, NPR 9998 as explained in Section 5.1. This choice was made for consistency with the index building models used to support the original fragility function development, described in Section 2.

- *Qualitative properties of masonry walls*. Degree of interlock between perpendicular walls and completeness of fill of mortar joints. These properties were assigned based on judgement on photos taken during building assessment (and subsequent demolition).
- *Concrete and timber floor and roof properties*. Stiffness and strength properties and reinforcement percentages based primarily on the judgement of experienced Dutch engineers.
- *Connections*. Stiffness and strength of wall ties and nailed connections. For timber–masonry connections, overlap dimensions, friction coefficient, mortar bond strength and pocket rotational stiffness were all considered.

3.4 Regression Approach and Fragility Functions

Collapse fragility functions were developed based on maximum likelihood regression of a lognormal CDF. Collapse states were identified for any analysis in which the normalised debris cover estimate exceeded 90%. Intensity measures considered were the spectral acceleration at 0.5 seconds (based on the original risk analysis) and 1.5 seconds (which was found to be a more efficient intensity measure for collapse prediction during this study – this observation does not necessarily hold for lower damage states). Variability was introduced in stages such that the effect of introducing (say) model variability on top of record-to-record variability could be quantified. The main fragility function shown for this building in Fig. 2(a) is for the case of a fixed base model (i.e. no SSI effects) with record-to-record variability and model variability included. Spatial variation of material properties was included, as described in [4] (although therein it was shown that results were not sensitive to this).

The range of model variability was considered to represent the actual uncertainty in the parameters of the specific house analysed, URM4L-1; additional parametric analyses described in the next section include geometric variations and other model modifications that are not found in the original house analysed, but which represent the wider uncertainty of parameter variations across the typology.

4 Approach to Typology-wide Building Variability

The fragility functions developed in [4] were intended to represent the uncertainty in the specific URM4L-1 study building. For example, geometric properties were for the most part not varied, since they were known for the specific building with high confidence. Parameters such as the degree of interlock in perpendicular walls and completeness of fill of mortar joints were varied to reflect the epistemic uncertainty in the quality of these specific details for the study building. In the case of these specific parameters, photos taken during the initial building assessments and subsequent demolition showed that there was variation in quality throughout the building; these parameters were therefore included in the spatial variation, referred to above.

Fragility functions appropriate for the entire URM4L typology may be expected to differ from those derived for URM4L-1 in two ways: (1) the mean of the fragility function may be different, if URM4L-1 is not representative of an "average" URM4L building; (2) the standard deviation is likely to be higher for a typology-wide fragility function, since it will include other sources of model variability, such as geometric changes.

Therefore, the approach adopted here was to decompose the building-to-building variability into: (1) variations in material properties, representative of variations for the whole typology, applied to a single index building (the study building described above); (2) variations in geometry, connectivity etc. found in a small pool of further index buildings. The distinction between these sources of variability is somewhat artificial (in reality, every building has its own geometry, connectivity and material properties), but taking this approach was found to be necessary to properly sample the typology. As noted in the Introduction, to address this, the approach taken in this work was to both expand the parametric variations on the original URM4L-1 study building to represent "typology-wide variations with the same overall building footprint and topology", and to introduce further index buildings to represent "typology-wide variations of building footprint and topology". These two sets of further analyses are described in the following two sections.

5 Additional Parametric Analyses on URM4L-1 (First Index Building)

Further LHS simulations were carried out on the URM4L-1 building model, incorporating modifications on assumed material properties, geometry, roof/attic material combinations, and other miscellaneous details. These are further described in the subsections below, followed by results and a discussion. Ground motion records were unchanged from those reported previously.

Due to the additional variability in the input parameters, 600 analyses were required to achieve stable fragility results (compared to 300 analyses required in the previous work). In the LHS method, this means that CDFs of model parameters are subdivided into smaller slices, and that each of the 100 ground motions are sampled 6 times.

5.1 Material properties

As noted in Section 3.1, the work reported in [4] used NPR 9998 code mean properties for CaSi and brick masonry, along with standard deviations rationalised from laboratory and field test data on the actual URM4L-1 building, or similar buildings. This decision was made because the work was being used to validate the simplified fragility procedure (referred to in Section 2), and it was important that mean properties were consistent with those previously adopted.

In the extended phase of work, mean and standard deviations properties based on the collected data were used to be more representative of the whole typology. Mean properties in the two phases are summarised in Table 1. It was also recognised that the coefficients of variation used previously represented the variations expected within a single building, since they were intended to apply specifically to the URM4L-1 house. When sampling across the range of parameters found in the whole typology, the overall variability for a given patch of masonry is higher, but there is correlation amongst samples within a given building (i.e. some houses have stronger masonry than other houses). Therefore, there is a "between-building variability" term that was sampled once per building in the Latin Hypercube, and a "within-building variability" that was sampled separately for each patch (see [4] for more on the treatment of spatial variation of material properties).

Table 1 – Mean masonry material properties used in previous work and this work

	Calcium Silicate		Clay	
	Previous	**This work**	**Previous**	**This work**
Young's Modulus	3.5 GPa	7.2 GPa	6 GPa	7.8 GPa
Compressive strength	7 MPa	10.4 MPa	10 MPa	15.8 MPa
Tensile strength	100 kPa	177 kPa	200 kPa	230 kPa
Shear strength	250 kPa	262 kPa	400 kPa	460 kPa
Friction	0.60	0.79	0.75	0.80
Other LS-DYNA inputs	Same		Same	

5.2 Geometric variations

The openings in the façade had previously been used as an indicator of potential vulnerability, as many modern terraced houses in Groningen have very large window openings, and very little structural wall to resist lateral forces. In fact, the URM4L typology was distinguished from the similar URM3L typology by the large openings in the façade. The original URM4L-1 index building had a façade openings ratio of 95% (based on the length of window divided by length of façade – a linear rather than areal measure of opening sizes). Two other openings percentages were included in the LHS simulation: 62% openings and 75% openings (discrete values based on the ease of incorporating into the existing finite element mesh). Discrete probabilities were assigned to these three values based on the approximate populations within the full URM3L and URM4L data sets from the Exposure Database (EDB) developed for the project [7].

The gable height is also very relevant for the out-of-plane stability of the gable. Again, discrete values of gable height were sampled (1.1 m, 2.2 m, 2.4 m, 2.8 m, 3.6 m and 5.0 m), with probabilities based on URM3L/URM4L data from the EDB. The weighted mean gable height was 2.8 m, which matches the value from the original baseline model for URM4L-1.

5.3 Roof/attic variations

The original URM4L-1 (and the actual house it was based on) had an attic floor and roof comprising timber purlins/joists and timber sheathing. When data for URM3L and URM4L typologies from the EDB were collected and assessed, it became apparent that this was a relatively rare system for buildings of this type. The most common combination was a concrete attic floor and timber plank roof, and other common combinations included plank roof with timber attic floor, and sheathed roof with concrete attic floor. Each of these four combinations was included in the LHS, with probabilities assigned based on the EDB data (the original URM4L-1 roof type was assigned a probability of only 1%, whereas the most common combination was assigned to 78% of simulations).

5.4 Miscellaneous details

The following other miscellaneous aspects of the URM4L-1 were varied:

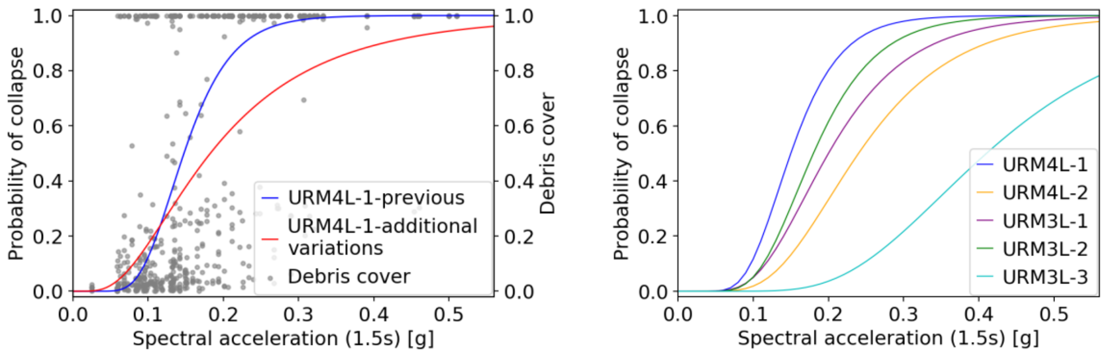
- *Internal walls*. The URM4L-1 did not have internal lateral-load resisting walls, although these had been observed in many buildings assigned to this typology. Specific data on this aspect was not available in the EDB; for lack of other information, lateral-load resisting internal walls were included in 50% of simulations.
- *Party wall anchors*. The URM4L-1 did not have party wall anchors between roof purlins, although these had been observed in many buildings assigned to this typology. For the same reasons as above, the two options (with and without wall anchors) were each assigned to 50% of simulations.
- *Corrosion of wall ties*. Wall ties connecting leaves in cavity walls have commonly been observed to be corroded in building assessments in Groningen. In the finite element modelling, corroded wall ties were assumed to resist no force. Based on the judgement of experienced Dutch engineers, a probability of corrosion of 15% was assumed. This was included within the spatial variation simulation; i.e. it was sampled individually for each patch, such that most simulations had some amount of corrosion, but none were fully corroded.

5.5 Summary of results

The fragility function developed for the revised analyses is compared with the results from [4] in Fig. 2(a). Values of debris cover from each of the 600 analyses are also superimposed on the same axes. As in the previous work, a threshold debris cover value of 90% was used to indicate full collapse. The main conclusions from these results are the following:

- Fragility is decreased (the median of the fragility function is increased) for the results with additional variations added. This may be at least partly due to the fact that material properties were generally stronger, as described in Section 5.1. Other model variations would also be expected to affect the fragility, although sometimes the effect is not self-evident.
- The variability (β value) is increased, reflecting the more variable range of buildings modelled. This increase in β is used to inform typology-wide fragility function development in Section 7.
- The debris data are significantly less binary than those reported in [4] – more intermediate values of debris cover between 0% and 100% are observed. Although the same 90% debris cover threshold was

used here for comparison with the previous results, other partial collapse states could be introduced with fragility functions evaluated with respect to lower debris thresholds. Alternatively, a continuous vulnerability model that does require the identification of discrete damage states could be fitted to the data [11].



(a) (b)

Fig. 2 – Fragility function results using Sa(1.5s) intensity measure based on debris cover > 90%. (a) URM4L-1 previous results compared with those with added variations (including superimposed debris cover data); (b) comparison of all index buildings

6 Additional Index Buildings

6.1 Index Building Model Descriptions

Four additional buildings were selected for analysis to support the development of typology-wide fragility functions. All were URM terraced house buildings with cavity walls and concrete floors. In the risk assessment, distinction was made between those terraced houses with a façade openings percentage greater than or equal to 90% (measured based on width of window and door openings divided by total façade width), and those with a lower percentage. The former were referred to as URM4L, and the latter as URM3L. Potential index buildings were selected from a pool of real buildings that had been analysed by Arup as part of a large programme of seismic assessments and upgrading. Only one other URM4L building was available, referred to as URM4L-2 herein. Three buildings from the URM3L typology – referred to as URM3L-1, URM3L-2 and URM3L-3 herein – were also selected. Relevant properties of each of the index buildings (including the original URM4L-1) are summarised in Table 2, and LS-DYNA models are shown in Fig. 3.

Modelling of the additional index buildings was the same as described for URM4L-1 in [4], summarised in Section 3.1. In the real buildings on which the URM4L-2 and URM3L-3 index buildings were based, the internal walls were constructed from a proprietary blockwork system, Bimsbeton blocks. For the purpose of the study, and because the behaviour of Bimsbeton under seismic loading is not well known, properties of Calcium Silicate walls were assumed.

Model parameters included in the LHS were the same as those assumed for URM4L-1 in the original study) [4] (i.e., they represent within-building variability for each specific building, and did not adopt the geometrical and other changes described in Section 5.

Table 2 – Summary of index buildings studied

Label	URM4L-1	URM4L-2	URM3L-1	URM3L-2	URM3L-3
Construction year	1976	1966	1971	1961	1963
Building mass (/ unit)	94 t	114 t	119 t	101 t	90 t
Total number of units	2	2	3	3	3
Front dimension	10.80 m	12.15 m	18.74 m	19.07 m	18.88 m
Side dimension	7.90 m	8.74 m	7.76 m	7.58 m	6.12 m
Roof gutter height	5.40 m	5.35 m	5.32 m	5.25 m	5.35 m
Gable height	2.80 m	2.41 m	2.35 m	2.11 m	2.23 m
Opening percentage	95%	90%	68%	68%	61%
First floor system	NeHoBo	2-way RC slab	1-way RC slab	2-way RC slab	2-way RC slab
Attic floor system	Timber	2-way RC slab	2-way RC slab	1-way RC slab	2-way RC slab
Structural internal walls	Gravity only	Lateral-load-resisting	Lateral-load-resisting	Lateral-load-resisting	Lateral-load-resisting
Roof framing	Timber purlins + sheathing	Timber purlins + planks	Timber purlins + planks	Timber purlins + planks	Timber purlins + planks
Other comments	Original building has 4 units; only 2 units modelled for symmetry				Floor slabs and inner leaf continuous between units; solid party walls

6.2 Fragility Function Results

Fragility functions developed for each of the five index buildings are shown in Fig. 2(b). Results for URM4L-1 are those from reference [4], and do not adopt the modifications from Section 5, for consistency in the comparison. The Sa(1.5s) intensity measure is used, and full collapse is based on debris cover exceeding 90%.

The main conclusions from this comparison are:

- The original index building, URM4L-1, is the most fragile of the index buildings studied, followed by URM3L-2 (which is only marginally more fragile than URM3L-1).
- URM3L-3 is significantly less fragile than the other buildings, which motivated a series of sensitivity studies. As noted in Table 2, URM3L-3 is unusual (with respect to the other index buildings) in that floor slabs and inner leaf of façade walls are continuous between house units, and party walls are solid (not cavity walls). The building also had the lowest openings percentage. The sensitivity studies concluded that each of these factors contributed to the extra resilience of URM3L-3.
- URM4L-2 is the second-least fragile of those studied; this result is unexpected because the URM4L typology is considered to be more fragile than URM3L in the risk assessment. It also shows the importance of considering multiple index buildings to understand typology-wide fragility.

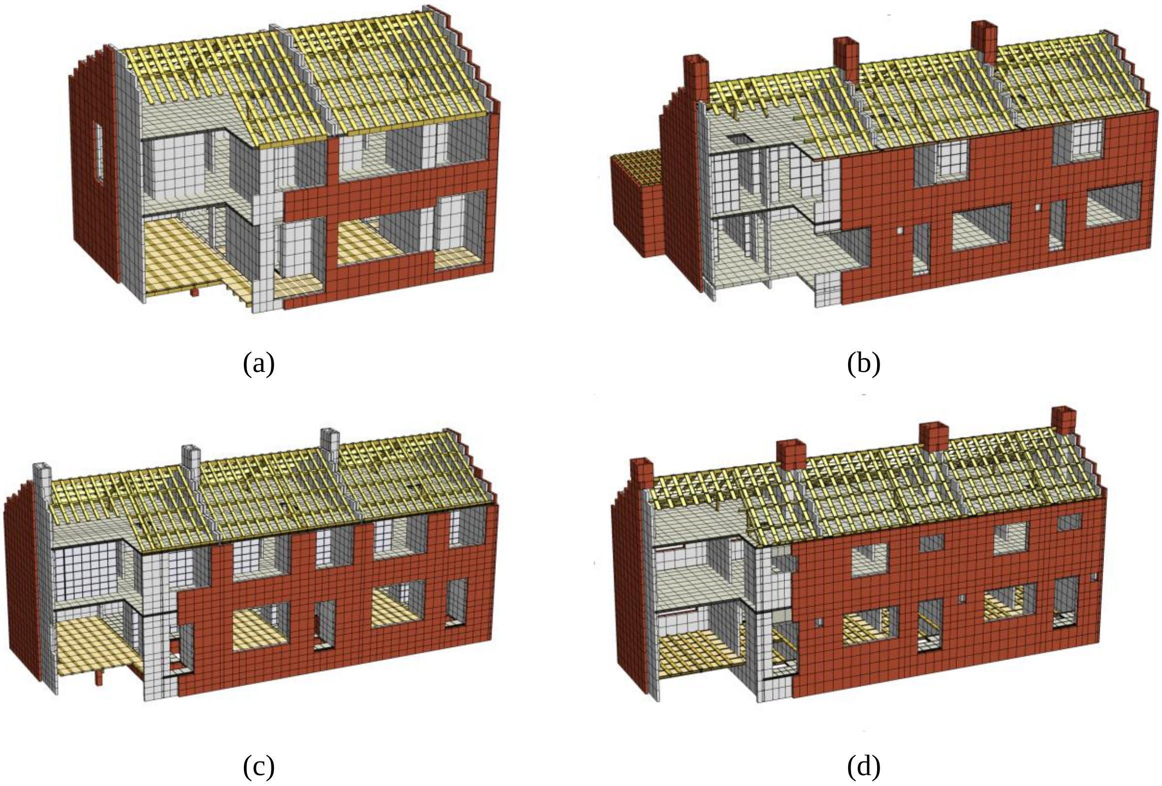


Fig. 3 – Additional index building models: (a) URM4L-2; (b) URM3L-1; (c) URM3L-2; (d) URM3L-3 (corner of models hidden to show internal details)

7 Combined Typology-Wide Fragility Results

7.1 Methodology

Typology-wide fragility functions were developed for URM3L and URM4L typologies separately, as well as a combined function representing both typologies together, based on the relative frequencies of buildings in each typology in the exposure database, and an extra component of variability to take into account the results reported in Section 5.

The methodology for combining index building results into typology-wide fragility functions was the following:

- For the individual typologies, each index building was given a uniform weighting (0.5 for the two URM4L index buildings; 0.333 for the three URM3L index buildings).
- For the combined URM3L/4L fragility function, each URM3L building was assigned 0.333 × 0.234 and each URM4L building is assigned 0.5 × 0.766, based on relative frequencies of each typology in the EDB.
- A combined fragility function was estimated for each intensity measure value as the sum of the weighted probabilities of collapse from each constituent fragility function. This combination of multiple index building results accounts for the differences introduced by layout, topology and building footprint.
- An additional uncertainty (β_{extra}) term was added with a square root sum of squares (SRSS) addition to represent the extra uncertainty due to typology-wide geometric and material variations. The additional term represents the variability introduced by geometric and structural system uncertainties, not included in the pool of index buildings. Its value was estimated partly based on the difference in the URM4L-1 results shown in Fig. 1(a); i.e. the difference between the work reported in [4] and that

reported in Section 5, and was taken as 0.3. (Note that this approach is equivalent to adding the additional uncertainty term to individual index building results and then combining; this was verified numerically).

- This gives a mixed formulation fragility function (i.e. one that does not follow a typical lognormal cumulative distribution function (CDF), which is required for use in both typical risk assessment software and in the specific risk calculation engine developed for this project). Therefore, a lognormal CDF was estimated using least squares regression, including only up to the 50th percentile results on the fragility functions. Focusing on the lower intensity/lower probability of collapse values in the regression ensured that the lognormal function is appropriate for the range of intensities driving the risk in the risk assessment model. The misfit between the mixed formulation and lognormal CDF fragility functions was verified to be small in the region included in the regression (i.e. up to the 50th percentile).

7.2 Results

Results for the typology-wide fragility functions are shown in Fig. 4. As could be expected from the methodology outlined in Section 7.1, the fragility functions have medians that are weighted averages of their constituents, and standard deviations higher than then individual index building results, accounting for both the extra variability (β_{extra}) and the differences between the medians. The median of the combined URM3L/4L fragility function is significantly skewed towards the results for the URM4L typology, due to the higher weighting factor assigned based on relative numbers in the EDB.

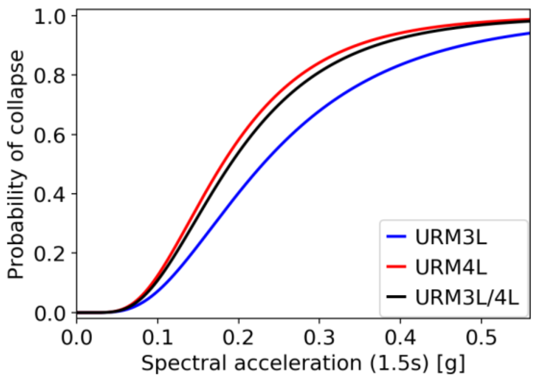


Fig. 4 – Typology-wide fragility function results

8 Conclusions

In this paper, an application of the development of fragility functions for a whole typology of URM buildings from analytical models of individual index building was summarised. The modelling and approach had been previously presented for a single index building in [4], and included explicit modelling of collapse and impact of falling components, explicit tracking and automated estimation of the debris cover inside the collapsing building models for use in casualty assessment, and variations in modelling and building parameters through a Latin Hypercube approach.

To estimate the fragility of an entire typology, the extra variability (beyond that of a single index building) was included in the study by decomposing into two components: (1) variability that can be expressed as modifications to the original index building (including gable heights, attic/roof system, openings percentage and a few other miscellaneous modelling assumptions); (2) variability related to the overall layout, topology and connectivity which is not amenable to a parametric approach. The first component was investigated by adding these other sources of variability to the Latin Hypercube, and comparing the results with those of the previous study reported in [4]. The second component was included by combining results from the original index building with those from analyses of four additional index buildings.

Finally, typology-wide fragility functions were developed based on weighted averages of the results from individual index buildings, with additional uncertainty introduced to reflect the parametric variations described above. Due to the availability of appropriate analysis models for the fragility assessment, separate fragility functions were developed for URM3L and URM4L typologies (both representing terraced houses with cavity walls and concrete floors, but differing in terms of the façade openings percentage), as well as a single fragility function representing the combined typology.

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