Determining fragility of urban low-to-mid rise masonry infilled building

S Sangadji¹, S A Kritiawan¹ and S I Prastiwi¹

¹Civil Engineering Department, Universitas Sebelas Maret, Surakarta, Indonesia

Email: s.sangadji@ft.uns.ac.id

Abstract. In seismic analysis of building, infill wall is usually modelled as non-structural elements and, hence, are not taken into account in analytical models. In general, engineers and scientists model these widely used structural system of masonry infilled reinforced concrete frame by considering the infill wall as load applied to the open confining frame. The presence of masonry infills, however, may significantly alter both the stiffness and the strength of the overall structural frame system. This present study aims to evaluate seismic performance of this type of building by developing fragility functions of the structure. Masonry wall was modelled as diagonal strut within the concrete frame. The masonry constituents and its composite properties were determined for the model. Then, the structure was subjected to incremental static lateral loading while adaptive pushover analysis was utilized to predict the response of the structure. As the damage states were defined from the spectral capacity curves, the fragility functions were developed for the structure. Effect of masonry wall included in the analysis was then compared to the results of open frame. The result of the eigen value analysis shows, the period for modelling a structure with an infill wall is smaller compared to modelling a structure without infill wall (open frame). This shows that the existence of infill wall elements in modelling increases the value of structural stiffness so that it reduces the period of the structure. Whereas, the results of the fragility curve in both structural modelling show that at some level of damage, the probability of damage for modelling structures with infill walls is smaller when compared to open frame. Realistic and rational results is presented in this work which show that modelling masonry wall with compression strut is beneficial.

1. Introduction

The geographical location of the Indonesian archipelago at the meeting of the four tectonic plates causes a high potential for natural disasters in Indonesia, one of which is an earthquake. The losses caused by the earthquake disaster were felt by many people. Many residential buildings, mostly moment resisting frame structure with masonry infill wall, collapsed or were damaged by the earthquake. This is due to the fact that most these typical low-to-mid-rise buildings are non-engineered and built based on the tradition and experience gained in the field, therefore does not meet the current standards and codes.

In analysing and designing these type of building, often engineers ignore the existence of a masonry infill wall. In general, planners do not take into account the infill wall as a structural component but are considered a uniform load applied on to the frame structure. However, the infill walls have a tendency to interact with the frame structure they occupy, especially if they are subjected to horizontal loads (earthquake loads). The presence of infill walls may affect the global stiffness and strength of building structures or its local component structural parameters. The real behaviour of the building may differ
from what it is predicted by the engineers analysing it using computer simulation. Studying the behaviour of these buildings system incorporating the masonry wall will help engineers to design it better and reduce its seismic risk. This paper elucidates the seismic risk evaluation of these low-to-mid-rise concrete moment resisting frame structure with masonry infill wall in term of its fragility given the ground shaking inputs during its service life.

In determining the fragility of a structure, it is required to determine the seismic response of the structure in question. Nonlinear Static Procedure (pushover) may be used to determine this response by producing a curve that relates base shear force with the displacement of the reference point of the structures, what is so called the capacity curve. The capacity curve then may be analysed and transform into capacity spectrum in the ADRS (Acceleration Displacement Response Spectrum) format, which in turn may be transformed into fragility curves. Fragility itself may be defined as the conditional probability that a structure exceeds certain limit of damage given the various earthquake intensity. The paper shows the fragility curves of the typical residential concrete moment resisting frame with or without masonry infill wall.

2. Literature review

Over the past two decades, researches have been carried out to study seismic behaviour of wall elements. In 1997, Francisco Javier Crisafulli [1] examined the behaviour of infill walls in reinforced concrete frames for earthquake loads. The study shows the non-linear behaviour of structures with infill walls against lateral loads. Meanwhile, the response of reinforced concrete frame structures with infill walls can be significantly increased in order to reduce the distortion of the wall panels when plastic joints are centred on a particular mass. C V R Murty and Sudhir K Jain [2] examined the benefits of the effect of the presence of walls on reinforced concrete buildings due to earthquake loads. They concluded that the wall increases strength, stiffness, overall ductility, and reduce energy dissipation from buildings when subjected to lateral loads (earthquakes). More importantly, the infill wall can significantly reduce deformation and ductility of reinforced concrete frames.

2.1. Seismic analysis

Seismic fragility assessment requires determination of structural capacity response. Non-linear static procedure (NSP) or pushover analysis is widely used method to obtain information about the capacity curve of a structure. The capacity curve is the relationship between the base shear and the displacement of the structure. In 2006, Rofooei and Attari [3] examined the comparison of the results of pushover analysis, adaptive pushover analysis, and time history analysis on several multi-bay steel structures for low-rise buildings and high-rise buildings. The results obtained indicate that the adaptive pushover method can provide more accurate results in determining story-drifts and plastic joint rotations in high-level building structures compared to the pushover approach. But the method of time history analysis can provide the best results when compared to pushover or adaptive pushover methods.

2.2. Masonry infilled wall modelling

In modelling masonry infilled wall, at least two general methods have been developed, namely micro-models (based on finite element methods) and macro-models (based on the Equivalent Strut method). Modelling using micro-models takes into account local effects in detail, meanwhile macro-models assumes the overall behaviour of wall modelled into diagonal compressive strut.

Some researchers carried out the analysis for the first time on masonry infill walls based on the theory of elasticity. Many have performed testing the masonry wall subject to compressive load. The idea was later developed that the effect of the wall on a frame due to lateral loads can be considered equivalent to the diagonal strut. Moretti [4] reported the compressive overview of the masonry infilled wall modelling development.

At present the diagonal strut model is widely accepted as simple but rational way to describe the influence of walls on moment resisting frame. The initial concept of the equivalent strut is only one
diagonal strut that connects two opposite angles to a wall panel. However, to represent the behaviour of cyclic loads, the diagonal struts are made at each panel angle, as depicted in the figure 1.

Figure 1. Masonry infilled wall modelling with compressive strut.

3. Research method

3.1. Building 3D modelling with software
In this study, structural modelling of both open frames and infill frames was performed using Seismostruct 2016 and depicted as figure 2. Seismostruct is a fibre-based finite element software that can predict a considerable behaviour of displacement from a structure subject to static and dynamic loads, taking into account geometric and material non-linearity. The parameter for the open frame structure in this study is the value of concrete compressive strength. Meanwhile, on modelling the structure with the infill wall the value of compressive strength of the wall panel was the key parameter.

3.2. Numerical modelling of masonry infilled wall
Four-nodal wall panel element was first introduced and examined by [1] which was then implemented on the Seismostruct, to model non-linear responses to the walls of the frame structure. The default modelling of the Seismostruct of each wall panel is represented by six struts, in the diagonal direction having two parallel struts which function to distribute axial loads in two diagonal angles on the opposite side and one buffer that serves to distribute the shear force from top to bottom of the panel. For axial load buffer, a hysteresis model was used, while the shear buffer is modelled using the bilinear hysteresis rule. There are 17 parameters that control wall panel element cyclic behaviour and four parameters that control their bilinear behaviour.
3.3. Loading
The load combination implemented in the model is dead load, live load according to Indonesian code SNI 1727-2013 [5] and seismic (pushover) load.

4. Results and discussion

4.1. Natural period of structure
Eigenvalue analysis was carried out to determine the dynamic characteristics of the structure. The analysis yields the natural period of the structure as expressed in the table 1.

| Mode | Open Frame | Infill Frame |
|------|------------|--------------|
| 1    | 0.509113   | 0.458465     |
| 2    | 0.490576   | 0.434689     |
| 3    | 0.452557   | 0.375313     |
| 4    | 0.164445   | 0.151227     |
| 5    | 0.15971    | 0.144653     |
| 6    | 0.147437   | 0.126064     |
| 7    | 0.093899   | 0.088215     |
| 8    | 0.092931   | 0.086065     |
| 9    | 0.086303   | 0.076582     |
| 10   | 0.068527   | 0.06582      |

It can be seen that the natural period of the structure modelled using the infill wall is smaller compared to the open frame model. This shows that the presence of walls in structural modelling alter the rigidity so that it reduces the natural period of the structure.

4.2. Capacity curve
The capacity curve is a curve that describes the relationship between the base shear and the displacement. Figure 3 shows the capacity curve yielded by pushover analysis modelled as open frame...
structures with concrete compressive strength for beams and columns of 22.5 MPa and structures modelled with infill walls with compressive strength of wall panels as of 0.9 MPa.

![Capacity curve of open frame and infill frame](image)

**Figure 3.** Capacity curve.

In the picture above, it can be seen that the presence of walls in modelling increase the value of the maximum base shear force of the structure. However, when the wall is damaged, the wall does not contribute to the rigidity of the frame and it will become an additional load that will push the frame in the lateral direction so that the base shear force of the structure has decreased significantly.

4.3. **Capacity spectrum**

The capacity curve in the figure 3 was then converted into a capacity spectrum curve which in turn would be further transformed into the fragility curve. The capacity spectrum curve shows the relationship between spectral acceleration (\(Sa\)) and spectral displacement (\(S_d\)). The values of \(Sa\) and \(S_d\) are obtained from the conversion of the base shear value and displacement on the capacity curve in the ADRS format by means of the equation listed in ATC-40 [6]. The results of the calculation of the capacity spectrum curve on both type of structural model can be seen in the following figure 4.

![Capacity spectrum](image)

**Figure 4.** Capacity spectrum (a) Open Frame (b) Infill Frame.

4.4. **Damage states**

In this study, two criteria for damage (limit) state were used, which are based on the: [1] performance criteria of the material and based on the [2] maximum base shear force of each model. The first damage
criteria were determined from strain limit values for concrete and reinforcing steel materials. The damage state, DS1, is defined from the point of the first yield on the reinforcement. Yielding on reinforcement occurs when the strain value in reinforcing steel is greater than the ratio between the yield strength and the elastic modulus of the steel material. In general, the maximum strain value used is 0.0025. DS2 is determined at the state of crushed unconfined of concrete section which occurs when the strain on the concrete surface (cover) is greater than the ultimate strain on the concrete surface when a crack occurs. In general, the maximum strain value used is -0.002. Whereas for DS3, it is determined when the concrete core begins to crush (crushed confined), i.e. when the concrete material strain is greater than the ultimate strain of concrete when unconfined, the value is -0.006. DS4 is determined from the point where the chord rotation occurs for the first time. The chord rotation value that occurs in the structure is automatically checked by the Seismostruct software.

While the second type of damage state based on based shear as reported by Silva et al. [7]. It was determined from the maximum basic shear force obtained from the capacity curve of each model. The first damage criterion (DS1) is determined when the base shear reaches 75% of its maximum value. DS2 is the maximum base shear force received. While DS3 is determined when the basic shear force decreases by 20% from its maximum value.

The value of damage state for the two criteria in each model can be seen in the following table.

| Table 2. Recapitulation of damage state. |
|-----------------------------------------|
| **Open Frame**                          |
|                                       |
| \( f'_c \) | \( f''_c \) | \( f''_c \) | \( f''_c \) | \( f''_c \) | \( f''_c \) | \( f''_c \) | \( f''_c \) |
| (MPa) | (m) | (m) | (m) | (m) | (m) | (m) | (m) |
| 35    | 0,0195 | 0,0481 | 0,1042 | 0,3297 | 0,0290 | 0,0912 | 0,4730 |
| 32    | 0,0195 | 0,0523 | 0,0998 | 0,3391 | 0,0291 | 0,0912 | 0,4730 |
| 28    | 0,0195 | 0,0523 | 0,0955 | 0,3141 | 0,0291 | 0,0955 | 0,4729 |
| 25    | 0,0195 | 0,0480 | 0,0955 | 0,3085 | 0,0289 | 0,0955 | 0,4723 |
| 22,5  | 0,0195 | 0,0480 | 0,0912 | 0,2931 | 0,0287 | 0,0955 | 0,4719 |
| \( \mu \) | 0,0195 | 0,0497 | 0,0972 | 0,3169 | 0,0290 | 0,0938 | 0,4726 |

| **Infill Frame**                        |
|                                       |
| \( f''_c \) | \( f''_c \) | \( f''_c \) | \( f''_c \) | \( f''_c \) | \( f''_c \) | \( f''_c \) | \( f''_c \) |
| (MPa) | (m) | (m) | (m) | (m) | (m) | (m) | (m) |
| 1,1   | 0,0198 | 0,0485 | 0,1005 | 0,1969 | 0,0500 | 0,1275 | 0,2046 |
| 1,0   | 0,0198 | 0,0485 | 0,1005 | 0,2017 | 0,0493 | 0,1275 | 0,2078 |
| 0,9   | 0,0197 | 0,0485 | 0,0962 | 0,2012 | 0,0487 | 0,1274 | 0,2128 |
| 0,8   | 0,0197 | 0,0485 | 0,0962 | 0,2058 | 0,0481 | 0,1319 | 0,2188 |
| 0,7   | 0,0197 | 0,0484 | 0,0918 | 0,2102 | 0,0595 | 0,1320 | 0,2277 |
| \( \mu \) | 0,0197 | 0,0485 | 0,0971 | 0,2031 | 0,0511 | 0,1292 | 0,2143 |

4.5. Structural uncertainty
The standard deviation for the total uncertainty of each damage condition \( (\beta_{ds}) \) is a combination of uncertainties in the boundary conditions for damage conditions, uncertainties in property capacity
structure reviewed and uncertainty in demand in the form of ground motion. Based on Hazus-MH MR [8], the total uncertainty of each damage condition can be calculated using the following equation (1):

\[
\beta_{ds} = \sqrt{\left(CONV\left[\beta_c, \beta_d\right]\right)^2 + \left[\beta_{M(ds)}\right]^2}
\]  (1)

where:
- \(\beta_c\) = standard deviation of the uncertainty of structural capacity
- \(\beta_d\) = standard deviation from the uncertainty of the demand spectrum
- \(\beta_d = 0.45\) for short periods and 0.5 for long periods
- \(\beta_{M(ds)}\) = the standard deviation of the uncertainty in the boundary value of damage conditions is taken as 0.4

Value of structure capacity uncertainty, \(\beta_c\) can be determined using the equation (2):

\[
\beta_c = \sqrt{\ln\left(\frac{s^2}{m^2} + 1\right)}
\]  (2)

where:
- \(m\) = average spectral structure acceleration capacity
- \(s\) = standard deviation of spectral structure acceleration capacity

The calculation results of the uncertainty values of each structure modelling can be seen in the following table.

| Structure Type       | Capacity \(\beta_c\) | Demand \(\beta_d\) | Damage State \(\beta_{M(ds)}\) | Total \(\beta_{ds}\) |
|----------------------|----------------------|---------------------|-------------------------------|---------------------|
| Open Frame           | 0.5662               | 0.45                | 0.4                           | 0.8265              |
| Infill Frame         | 0.5652               | 0.45                | 0.4                           | 0.8258              |

4.6. Fragility curves

The fragility curve describes the probability that a building and or its component exceed a certain damage level given various demand parameters, e.g. earthquake intensity, such as peak ground acceleration (PGA), etc. The equation used to determine the conditional probability of damage condition if the spectral displacement is used is expressed in the equation (3):

\[
P[ds \mid S_d] = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right]
\]  (3)

where:
- \(P\) = probability of structural damage
- \(\bar{S}_{d,ds}\) = the median value of the spectral displacement achieved by a building at a certain level of damage, ds
- \(\beta_{ds}\) = standard deviation of lognormal spectral displacement
- \(\Phi\) = the standard function is normal cumulative distribution

The results of calculation of fragility curves for open frame structures and infill frames on all four damage states according to strain limits of concrete and steel materials can be seen in the following figure 5.
Figure 5. Fragility curves based on strain limit criteria.

The probability values for both types of structures are almost the same for DS1, DS2 and DS3. This is because the presence of walls does not affect the strain limit values of concrete and reinforcing steel materials. So that the difference in the point of the first melting on the reinforcement, the crack on the concrete blanket and when the concrete core is broken on the two models is not very significant, so the resulting fragility curve will coincide. While the probability of damage to the open frame structure on DS4 is smaller when compared to structures with walls. This can happen because the limit value used on DS4 is the chord rotation. In structures with infill walls, when the wall element is damaged, the wall will become an additional burden that pushes the frame in the lateral direction, resulting in faster chord rotation when compared to structures without infill walls.

The results of the calculation of the fragility curve for open frame structures and infill frames for three damage states according to the maximum base shear on the capacity curve can be seen in the figure 6.

Figure 6. Fragility curves based on maximum based shear according to Silva et al.
At DS1 and DS2 damage limit values the probability of damage to structures without infill walls is greater than structures with infill walls. For example, when Sd is 0.4 m, the probability of damage to structures without infill walls on DS2 is approximately 96%. Whereas the same Sd value for structures with infill walls has a probability of damage of approximately 91%. But in the type of DS3 damage, structures without infill walls have a smaller probability of damage than structures with infill walls. This happens because in modelling the structure with the infill wall, when the wall has been damaged and cannot contribute to stiffness in the frame, the wall will be a burden that pushes the frame towards the lateral so that the base shear value will decrease significantly.

5. Conclusion
From the results of the analysis, the following conclusions are obtained. The results of the fragility curve analysis on both structural modelling (without walls and with walls) were carried out using two criteria to determine damage state, which is based on the strain limit values of concrete and steel materials and the damage limit value according to Silva et al. which refers to the maximum base shear force.

In the analysis of fragility curves using damage criteria in the form of strain constraints of concrete and reinforcing steel materials, it cannot provide significant information about the presence of walls in structural modelling. However, in the analysis of fragility with damage criteria according to Silva et al. which refers to the maximum basic shear force of the structure, it can be seen that in some damage conditions, the presence of walls in modelling can affect the behaviour of the structure when exposed to earthquake loads.

The presence of infill walls on a frame can increase the strength of the structure. This can be seen from the results of adaptive pushover analysis in the form of a capacity curve on each model. Where the value of the maximum basic shear force that can be accepted by the structure by modelling using the infill wall can increase significantly. From the results of the fragility curve of each structure, in some conditions the damage to the structure with infill frames has a smaller possibility of damage compared to modelling without a wall of infill (open frame).

For further research some suggestions are provided. It is necessary to validate values by conducting laboratory tests on several parameter values that control the behaviour of the strut on wall modelling so that it can be more adapted to the material in Indonesia. In further research, you should take into account the presence of openings on walls such as doors and windows so that the results of the analysis can approach the actual conditions in the field. Determination of damage state values in seismic structure fragility analysis procedures is the most important and critical process. Determination of this value affects the results of the structure fragility curve. Therefore, the approach in determining this boundary value needs to be supported by careful analysis of structural responses when receiving seismic loads.

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