Numerical Analysis Tools for Modelling Reinforced Concrete Shear Wall Buildings Subjected to Earthquake Loadings (E6953)

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1 Summary

When it comes to resist lateral loads, shear wall is a preferred structure form. The are two main categories of finite elements to model seismic reposes of reinforced concrete shear walls, namely the microscopic and macroscopic elements. These numerical tools suffer from several vital problems, such as accuracy, efficiency, reliability and applicability, which hinder their engineering applications.

Both experimentally and numerically, it is shown that the in-plane axial-flexural-shear interaction does exist in wall panels. It is not applicable to simply neglect its effect since it could contribute up to 50 % of total deformation for short walls. However, it cannot be well predicted by current macroscopic wall elements yet. By definition, available 1D macro elements, in which heavy use of spring/truss elements is involved, cannot fully reproduce the non-linear shear response/profile along the horizontal direction due to the '*plane sections remain plane*' assumption which is unavoidable during the process of simplifying a 2D planar problem to a 1D one. Another severe issue is the capability of simulating wall-frame interaction. Although some simplification methods have been proposed for hand calculation, it is still complicated to develop finite element models to handle the interactions between wall panels and beams/slabs by using current macro elements, due to the lack of in-plane rotational degrees of freedom.

This project aims to solve above two drawbacks. The main objective is to develop an efficient quadrilateral shear wall element. The new element should be capable of reproducing coupled in-plane **axial-flexural-shear interaction** with reasonable coarse-mesh accuracy subjected to high shear stress and allowing straightforward simulations of the **wall-frame interaction** without any additional configuration.

The proposed (S)GCMQ element is developed based on a modified generalised variational theorem. The Hu-Washizu variational principle is used as a basis, the drilling degrees of freedom are introduced into the formulation by a proper decomposition of deformation. The generalised conforming approach is adopted to simplify the formulation. By selecting and optimizing the interpolation functions of stress, strain and displacement fields, GCMQ and SGCMQ elements are formulated. Furthermore, under the proposed variational framework, a series of elements can also be constructed by selecting different shape functions. A five-point integration scheme is also proposed to save computational effort. Since (S)GCMQ a planar element, it can automatically take all three in-plane stress components into consideration as long as the associated material model supports refined material behaviour. By this manner, the interactions among different stress components can be represented.

The validations of (S)GCMQ are performed via selected elastic/plastic problems. Simulations of available shear wall specimens/structures are conducted with proper material models in the calibration section. (S)GCMQ is free from shear and volumetric locking and shows good bending performance. (S)GCMQ also improves the tolerance to mesh distortion. (S)GCMQ exhibits good coarse mesh accuracy so that it can be used in practical applications with a relatively low computational cost. Without loss of generality, (S)GCMQ provides an efficient alternative to numerical simulations of reinforced concrete shear walls.

2 Introduction

The circum-Pacific belt (**Ring of Fire**) is an active seismic zone. Many earthquakes occur in this region. Of the earthquakes, 6 out of 17 largest earthquakes since 1900* occurred during this century. New Zealand is located at one end of the circum-Pacific belt, two faults (the Alpine fault and the Wellington fault) run the length of the country, which makes it to be frequently struck by earthquakes.

The most recent hazardous earthquake in New Zealand is the Christchurch earthquake occurred at 12:51 p.m., on 22nd February, 2011. The event caused collapse of two multi-storey buildings and killed 185 people in total. Detailed investigations of failure mechanisms of collapsed buildings can be found in the reports by Royal Commission (2011b,a), Jury (2011) and Kam and Pampanin (2011). During this earthquake, a shear wall, located on the ground floor of Hotel Grand Chancellor (HGC) building, experienced high torsional actions and finally failed due to out-of-plane buckling. The failure *came close to causing a catastrophic collapse of the building* (Royal Commission, 2011b). Wall failures due to all kinds of mechanisms, such as shear failure and concrete crushing, were also observed in recent earthquakes in Chile. Specific analyses and discussions could be seen elsewhere (Carpenter et al., 2010; Wallace, 2012).

It could be noted that the tensile flexure failures are rarely observed in these earthquakes. This is possibly due to the fact that, after extensive research, structural engineers have gained comprehensive understanding of flexural behaviour of shear walls. Consequently, the flexure capacity is well designed and the corresponding failure patterns can be successfully suppressed. In contrast, engineers have limited knowledge about the

*Please check USGS database. https://earthquake.usgs.gov/

shear behaviour of wall panels due to its inherent intricacy. In practice, the shear response is assumed to be elastic and its effect is thus often neglected, particularly for slender walls. However, under some particular circumstances, such as high shear stresses and/or low aspect ratios, shear deformation may contribute a considerably significant amount (up to 50 %) to the total deformation, particularly after shear yielding. Such phenomena were observed in a number of experiments (see, e.g., Oesterle et al., 1980; Thomsen and Wallace, 2004; Tran and Wallace, 2015).

For numerical analyses, it is, in general, a difficult task to model shear walls due to the intricacies of both the corresponding geometries and material properties. Although both global and local responses could be generated by using general purpose microscopic[†] finite elements in commercial finite element analysis (FEA) packages (see, e.g., Kazaz et al., 2006; Palermo and Vecchio, 2002, 2004, 2007), it is impractical to use these elements to conduct simulations of large scale structures due to efficiency problems (Orakcal et al., 2004). To date, engineers still prefer to use macroscopic elements for shorter analysis times.

Unfortunately, most of current macroscopic shear wall elements can only be used at the global level. By definition, macroscopic elements are incapable of predicting refined in-plane coupled response. This is also pointed out by Fischinger et al. (2004). Essentially, they are 1D elements that take displacements along element axes/chords as inputs and use 1D material models to compute response. The transverse response cannot be taken into account by the material models used. Although some macroscopic elements that incorporate 2D plane stress material models have been proposed recently, they cannot be used in practical simulations due to other numerical deficiencies. For example, to produce transverse shear response, some elements attempt to construct **biaxial** strain based on **uniaxial** displacement inputs. Since the biaxial strain formulated in this way lacks a mechanics basis and may not be able to describe the true strain field, such an approach is nothing but GIGO (garbage in garbage out, computer science terminology) no matter how good the adopted material model is. Thus, almost all numerical simulations of low-

[†]There are no consensual definitions of macroscopic and microscopic elements. In the following context, all 1D elements, including any spring and beam based elements, are categorized as macroscopic elements. 2D elements that are formulated according to continuum mechanics and converge to analytical solutions with mesh refinements are referred to as microscopic elements.

rise walls were carried out by using microscopic elements (see, e.g., Gulec and Whittaker, 2009).

As pointed out recently by Wallace (2012), additional numerical investigations, particularly at the macroscopic level, are still needed for shear walls with low aspect ratios subjected to significant shear stresses. As can be seen later, the current macroscopic elements also suffer from several vital problems, such as incomplete coverage of failure mechanisms due to the 'plane sections remain plane' assumption, lack of capability to account for wall-frame interactions and out-of-plane response. Thus, an efficient element that can ease those problems is still in demand.

3 Objectives

The main objective of this work is to develop a new finite element that exhibits high performance for modelling tasks of panel like 2D structure members, such as shear walls. According to Wriggers (2008), to develop a new continuum element with good performance, the following objectives shall be met.

1. locking free behaviour for incompressible materials,
2. good bending performance,
3. no locking in thin elements,
4. no sensitivity against mesh distortions,
5. good coarse mesh accuracy,
6. simple implementation of nonlinear constitutive equations and,
7. efficiency (e.g., fewer integration points).

Apart from the above objectives, it is preferable for the new element to have only corner nodes to simplify the meshing process and minimise the sizes of global matrices. It is also preferable to include in-plane, drilling, rotational degrees of freedom (DoFs) into the new element. The presence of drilling DoFs can be utilised to address the compatibility issue existing in modelling wall-frame interactions. Elements with midside nodes are not suited to dynamics or large deformation problems (Belytschko et al., 2014). Furthermore, analysts are interested in not only displacement but also strain and stress results. The capability of simplifying the recovery of better strain and stress distributions is also desirable.

4 Conclusions

In this work,

1. A four-node quadrilateral membrane element with drilling degrees of freedom named as GCMQ is proposed.
2. A simplified version of GCMQ, named as SGCMQ, is proposed for better numerical efficiency.
3. A five-point integration scheme is proposed to minimise the computational cost.

The proposed (S)GCMQ element combines the advantages of both the mixed formulation and the generalised conforming method. Up to three enhanced strain modes are supported by the formulation. In the proposed elements, GCMQ adopts one enhanced mode while SGCMQ excludes the enhanced mode. Alternatives are possible. Elastic validations of the proposed (S)GCMQ element have been performed with emphases on convergence, mesh distortion sensitivity, shear locking, volumetric locking and coarse mesh accuracy. The objectives are mostly fulfilled, (S)GCMQ has the following features.

1. free from volumetric locking,
2. good bending performance,
3. no locking in thin elements,
4. very low sensitivity to mesh distortions,
5. good coarse mesh accuracy,
6. simple implementation for nonlinear constitutive equations and,
7. minimised computational cost.

In the meantime, (S)GCMQ exhibits high coarse mesh accuracy that can be utilised in both elastic and elasto-plastic applications. Since (S)GCMQ is a general-purpose planar element, it can be used to model not only reinforced concrete shear walls but also other 2D problems. The finite element analysis is more efficient with (S)GCMQ since the number of DoFs required to achieve the same level of accuracy can be significantly reduced.

Due to the presence of drilling DoFs, (S)GCMQ can be used with other types of elements without additional treatments. This feature can be utilised to simplify the pre-precessing procedure of some special applications such as the simulation of wall-frame structures in civil engineering. The drilling DoFs are also advantageous when it comes to forming a planar shell element by combing (S)GCMQ with other plate elements. The corresponding stiffness matrix would be properly ranked, no other numerical considerations are required.

5 Discoveries

Several applications of (S)GCMQ with nonlinear material models subjected to static, including both monotonic and cyclic, and dynamic loadings are also performed to model squat/short and slender shear walls, as well as weakly coupled shear walls. Various mesh configurations are examined. Several discoveries can be concluded as follows.

1. Convergence is guaranteed for (S)GCMQ with different integration schemes. If dense meshes are used, the five-point adapted Irons quadrature is preferable due to its minimised numerical cost.

2. For most examples shown in this dissertation, there is no significant difference observed from the results of (S)GCMQI and (S)GCMQL. Since displacement, strain and stress are interpolated internally, the additional four integration points used in (S)GCMQL do not lead to any improvement of performance. In this sense, (S)GCMQL is not recommended unless some other material properties are of interest.

3. The proposed (S)GCMQ element has a lower initial error bound, which is advantageous in terms of elastic applications.

4. The performance of drilling degrees of freedom is reliable **only** when the wall-panel connection is properly sized. It is thus recommended to model weak coupling effects by using membranes and beams while for strong coupling members complete 2D models with plane stress elements shall be employed.

5. The performance of (S)GCMQI/(S)GCMQL differs from that of (S)GCMQG due to the different arrangements of integration points. It is a common phenomenon and hard to determine which one is consistently better than the others. It is thus the analysts' choice to decide which version to use.

6. (S)GCMQ element is able to produce more accurate eigenvalues, viz., natural periods of structures, with fewer elements. This is advantageous when it comes to eigenanalyses of structures. In terms of mass formulation, no significant difference is observed among different formulations for lower modes. However, it is recommended to use full ranked mass matrices to accommodate some conditionally stable time integration algorithms.

7. The overall performance of numerical simulations relies on not only elements but also material models. It could be seen that objective results can only be obtained by using material models that support regularisation. In other words,

$$\text{High-performing Element} + \text{Objective Material} = \text{Good Overall Accuracy}.$$

Apart from the sensitivity to severe mesh distortion, it is worth noting that there may exist a stability issue when the enhanced strain is present. The problem can only be observed with **certain** nonlinear material models. It may be related to the common issue with enhanced strain elements as discussed by Wriggers and Reese (1996). Numerical experiments reveal that the convergence rate would be greatly affected even with the presence of consistent tangent stiffness. However, convergence can still be achieved and the solution can be computed. In specific, the problem appears with GCMQ (no matter how many enhanced strain modes are used) and the CDP model. All other material models used in this work do not exhibit unstable performance. Based on these facts, GCMQ is recommended for linear analysis while SGCMQ is recommended for nonlinear analysis.

6 Impact

With the proposed element, the simulation of reinforced concrete shear walls requires less computational cost. By such, it is possible to perform numerical analysis of large scale wall structures on personal computers with acceptable amount of time. This efficient numerical approach can be utilized by civil/structural engineers for optimal design of structures. It also enables researchers to gain a better understanding of wall response under seismic loadings, especially when the corresponding experiments are not available. All these aspects would improve the robustness of buildings subjected natural hazards such as earthquakes.

7 Future Work

The formulation of the (S)GCMQ element is based on an additive decomposition of infinitesimal deformation. The distortion $\boldsymbol{u}_d$ can be directly constructed on the translated configuration $\boldsymbol{x}_m$. Hence, a finite deformation formulation can be further developed by keeping the second order term $\nabla\boldsymbol{u}_d\cdot\boldsymbol{u}_t$. Although finite deformation may not be critical for structural walls in civil engineering, it could be useful in other applications.

For simplicity, only one enhanced mode is adopted in GCMQ while the formulation supports at most three modes. A more extensive study of different enhanced modes can be performed in order to seek potentially better modes that can further improve the coarse mesh accuracy of GCMQ.

It could been seen that the proposed (S)GCMQ element shows a very good performance among existing four-node quadrilateral membrane elements. Though, for 3D applications with arbitrary planar geometries, a shell element is in demand. SGCMQ can be readily combined with other plate elements to form high performing shell elements. Since the plate theory has been extensively investigated by researchers to date, there are a lot of very good four-node plate elements in current literature. Successful ones, such as DKT element family (Batoz et al., 1980), can be directly borrowed.

It can also be concluded from numerical examples that the adopted definition of drilling degrees of freedom is not perfect. It works well when the distortion is not great compared to the translational deformation. However, in the current context, there is still a lack of theoretical basis for discussions of the 'precision' of the drilling DoFs. Ideally there shall be two drilling DoFs per node to control the distortion of two connected edges respectively. It is thus possible to develop a series of different types of elements with four DoFs per node to form a new finite element system, which may help to improve the numerical representation of realistic deformation field.

As discussed previously, apart from the element aspect, the development of a good in-plane (or 3D) concrete material model that supports flexible definitions of hysteresis rules and damage evolutions is still challenging. The two-surface plasticity theory (Dafalias, 1986) combined with the damage mechanics would be an appealing potential. In terms of modelling reinforced concrete problems, to accommodate more flexible definitions of reinforcement layouts, it is possible to define some built-in patterns of reinforcement that may adopt both discrete and smeared approaches. A laminated membrane/shell element could be constructed atop (S)GCMQ.

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9 Publications

1. *A new drilling quadrilateral membrane element with high coarse-mesh accuracy using a modified Hu-Washizu principle* **International Journal for Numerical Methods in Engineering**

   doi: 10.1002/nme.6066

2. *Numerical evaluations of a novel membrane element in simulations of reinforced concrete shear walls* **Engineering Structures**

   doi: 10.1016/j.engstruct.2019.109592

10 Potential End Users

The proposed element is a general-purpose finite element that can be used in numerical simulations of various planar problems. Structural engineers can use the element to model the response of shear walls. Geotechnical engineers can utilise the element in the simulation of soil related problems. Researchers who work in the related area can also make use of the proposed element to investigate the behaviour of some panel-like objects.

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