The stability of slender masonry mullions

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Abstract

During the building of the great cathedrals of Europe, masons endeavoured to produce larger windows with more slender mullions, so as to flood the building with natural light. These were later glazed with stained glass, giving rich colours to the interiors. There is limited anecdotal reference to window collapse; however, one of the larger windows in Durham Cathedral has an internal masonry frame which appears to have been constructed to provide added resistance of the window to inward collapse under severe wind loading. This curious architectural detail is the reason for this study into window stability. Two windows in Durham Cathedral have been studied to consider their factors of safety against mullion instability.

1. Introduction

Since Mediaeval times, masons and architects have extended their skills and experience into larger windows, with taller and more slender masonry mullions. As the use of stained glass panels spread from Venice throughout Europe the great cathedrals and churches used large windows as an essential architectural feature. These tall slender windows also evolved into different forms, such as the circular or 'rose' window. The section through mullions appears to have been refined with the years, so that in the great cathedrals the appearance of the mullion is minimised by reducing the facets on view to a minimum; this is structurally highly inefficient.

The mullions of the several forms of window appear to have evolved through the skills of the master masons, rather than by calculations of architects or engineers. The limits on slenderness ratio appear to have been set by experience, which probably implies knowledge of failures of mullions under severe wind gust loading. There is little anecdotal evidence of failures. However, an example of remedial building, presumably to increase resistance to wind-induced failure, is
provided in Durham Cathedral. The St Joseph window has a free-standing additional arch support inside the transepts.

Durham Cathedral is a splendid Norman building dating from 1093, and is constructed from local sandstone. Information on its structure is available in Pevsner [1], and Jackson [2], and many other local publications and guides.

1.1 The structural action of a masonry mullion

Mullions are tall slender masonry columns or spars, which span between the massive masonry construction of the main wall construction. They support panes of glass, which are subjected to strong gusts of wind. Durham Cathedral has stood high above the river Wear for over 900 years, and will have experienced extreme pressures from wind loads. However, the mullions do not act as simple beams in resisting wind pressure, because of their constraint within the massive walls. Instead, each mullion acts as a very shallow arch, which can fail only by 'snap-through buckling', see Figure 1.

![](image)

Figure 1. Schematic of failure by snap-through buckling.

The major difference from simple bending is the end restraint from the walls which prevent any expansion, but the weak mortar joints give only very small tensile strength. This failure mechanism is possible only if local crushing or spalling occurs in the very localised areas where cracks start to open.

The initial concept of failure was that resistance to deformation would continue to increase until the maximum displacement was equal to the thickness of the mullion. At this point the line of action of thrust would move outside of the section, and the mullion would fail explosively. This deformation could be computed for any mullion and hence safety factors could be estimated. However, this concept was unproven, and in addition some allowance would be necessary for any local crushing of the areas near to cracks, and for an effective modulus of the combination of sandstone blocks and mortar joints. Consequently some
laboratory tests were considered necessary for calibration of the following FE analyses.

2. Laboratory tests

A series of tests was conducted, in which 50mmx50mm concrete blocks were placed between very stiff end blocks which were designed to limit any extension. The blocks were tested with un-mortared joints, and with mortar joints of 2mm, 4mm and 8mm thickness. A lateral point load was applied until snap-through failure occurred. Two example sets of load displacement curves are shown in Figure 2. Each set of curves relates to displacements at 1/8, 1/4 and 3/8 of span and mid-span, or 1/6, 1/3 and 1/2 span, terminating in snap-through collapse.

Unmortared joints:

![Unmortared joints graph](image1)

4mm mortar joints:

![4mm mortar joints graph](image2)

Figure 2. Load-Displacement curves for blocks with no mortar and with 4mm thick mortar joints.
Figure 3. Mullion failure load as a function of mortar thickness of the joints.

It was clear that the failure load reduced with thickness of the mortar joints, Figure 3, indicating that the local crushing of the mortar joints contributed significantly to the deflections toward the critical position.

However, it was observed that in all the tests the critical deflection was approximately 1/3 of depth, rather than the initially anticipated full depth. This offers a rather tenuous link to the 'middle-third' rule for a section in eccentric compression which introduces tension when the eccentricity exceeds one third of the section depth. This primary result was carried forward to the FE computations of mullion deflection.

3. Finite element modelling of snap-through buckling

True analysis of buckling of a masonry-mortar mullion by finite elements is not a simple or reliable exercise. Instead, it was decided to use the laboratory results to calibrate FE analysis using effective moduli, and with a failure criterion of instability occurring at maximum deflection of 1/3 of section depth.

3.1. FE analysis of laboratory mullion models.

Modelling of the approaching failure of a masonry mullion model required an iterative procedure. Firstly, a simple plane stress model of the mullion (as seen in side elevation) was constructed, with a half-model utilising symmetry, and with care to prevent longitudinal expansion. A small central point load was applied, and longitudinal stresses were computed. By inspection, elements were identified where the longitudinal tensile stress exceeded the nominal mortar tensile strength. These nodes were then released, and a crack was introduced in each zone. The model was then loaded with a higher load, and the process was repeated.
When the deflection of the partially-cracked mullion reached $1/3$ of section depth, failure was assumed. A deflected mesh of 8-noded elements is shown in Figure 4, together with contours of longitudinal stress, which show the development of a shallow arch of compressive stresses.

### 3.2. FE analysis of the St Joseph window, Durham Cathedral

The FE analysis of the vertical mullions within the St Joseph window was essentially similar to those used for analysing the laboratory models. However, the scale of the mullion was to full size, being some 5m tall. The FE model was a simplification of the full ornate stonework, Figure 5, and was assumed to be a single vertical column.
A further simplification was that the mullion cross-section was assumed to be rectangular, rather than tapered and sculpted towards each facet. An appropriate value of modulus of stone plus mortar was assumed. Finally the loading on the mullion was taken to be a uniform load due to wind gust pressure on the adjacent glass panes. A value of peak gust pressure during a one-thousand year return period was calculated using CP3 Chapter 5 [3], to be 2880 N/m².

The factor of safety calculated against snap-through buckling, with the above limiting assumptions, was 2.8. This is a comfortable value, and it is rather surprising that a Cathedral Architect of many years ago had made the decision that an internal arch was needed to give additional resistance to window instability.

3.3. FE analysis of the Rose window, Durham Cathedral.

The Rose window, located high in the East end wall of the Cathedral is some 8.6m in diameter. It comprises a central glass boss, 12 inner tapered segments, 24 outer zones, and some small outer edge make-up pieces.

![Figure 6. The Rose Window, Durham Cathedral.](image-url)

Although not as old as the nave and transepts which are 900 years old, it is a major feature of the Cathedral, Figure 6. The slender stonework for the fenestration comprises sandstone piecwork some 400mm deep but only 140mm thick overall, and tapered strongly to facets only 50mm wide.
fenestration comprises sandstone piecework some 400mm deep but only 140mm thick overall, and tapered strongly to facets only 50mm wide.

FE analyses were conducted broadly as before, for the case of snap-through of a single major mullion 3500mm long, running from the boss frame to the outer massive wall. Again care was taken to model the behaviour in which longitudinal expansion was prevented. Wind gust pressure on the glass panes now had to be distributed in a non-uniform pattern appropriate to the areas of glazing which framed onto the main mullion. Computation of a factor of safety in excess of 10 indicated that the mullion would not fail in this mode.

However, a second mode of failure was investigated, in which the central stone boss moved inwards uniformly. The consequent snap-through now consisted of a four-hinge failure with a span of 8600mm, see Figure 7. A factor of safety of 3.0 was estimated against this mode of snap through buckling.

Figure 7. Schematic failure of the entire Rose Window.

Figure 8. Computed displaced shape and contours of longitudinal stress, Rose Window
The computed displacements are rather different to previous analyses, however the formation of a shallow arch can be seen in the plot of longitudinal stress contours, Figure 8.

A safety factor of about 3.0 is adequate, and is due to the depth of the stone section. It is a testimony to the very high quality of the workmanship of the masons that the only repairs which have been needed relate to degradation of the sandstone during Victorian times, when smoke levels in the air were severe.

4. Conclusions

The stability of slender stone mullions against strong wind gusts has been investigated. The mode of failure has been identified as 'snap-through' buckling because of the nature of the restraint provided by the massive walls to the ends of the mullion.

Laboratory tests on concrete blocks with thin mortar joints have demonstrated that this form of structural behaviour does occur. Further, the tests showed that instability was initiated when the deflection was equal to about 1/3 of the mullion thickness.

The laboratory results were used to calibrate FE simulation of the formation of a shallow arch, the formation of tension cracks, and its deflection under load.

The calibrated FE analyses, and the modified failure criterion, were then applied to two windows in Durham Cathedral, when the windows were subjected to severe gust loads with a 1000 year return period. The windows were estimated to have adequate factors of safety against snap-through buckling.

Further work is under way to estimate the beneficial effects of the self-weight compressive stresses during normal column construction, and also to study mullions with higher slenderness ratios.

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References

