Tall modular buildings: height limits of stacked steel modules

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Introduction
Modular buildings are made from room-sized units produced in a factory and assembled on site [1]. Their “off-site” nature can help to accommodate increasing population and urban density in cities [2], if these buildings can become much taller. Existing modules can consist of either thin structural walls or beams and columns, as shown in Figure 3. The modules can then be stacked, forming a modular building [3].

Methodology
A single stack of perfectly connected steel modules was investigated – a modular tower. Figure 2 shows the loadings considered. Different generic module types were investigated, as shown in Figure 3; variations in manufacture were also considered.

Case studies
Heights of existing tall modular buildings were compared with predictions.

Figure 2 Modular tower, with vertical and horizontal loads [4]

Project aims
The following aims are considered:
• To find the height limit of simple stacked modular buildings.
• To find the variation of this height limit between different types of module.

Figure 1 Thin-walled module (a) and frame module (b) [3]

Results
Figure 7 shows an Ashby Chart of maximum number of storeys vs weight of module in each tower. Each point on the chart is a different modular tower, coloured accordingly; clusters of the same module type have been highlighted. Solid block modules (blue cluster) give maximum height but are very heavy (and unrealistic), Thin-walled boxes (red cluster) give modules generally lighter than the other module types (furthest to the left of the plot). Braced frame modules (yellow cluster) give a similar maximum height as thin-walled boxes, but have a larger weight variability. Unbraced frames (green cluster) generally give heavier modules than thin-walled boxes, but also give the tallest practical tower at 78 storeys (see Figure 7). A summary of the results is given in Table 1 showing this unintuitive result – the unbraced frames greatly outperformed the braced frames as well as the thin-walled boxes. The reason is because the sections used in the unbraced frame may work better in bending than when pinned and braced, as demonstrated in Figure 8 for a single storey.

Table 1 Summary of results

<table>
<thead>
<tr>
<th>Module type</th>
<th>Tallest (no. of storeys)</th>
<th>Lightest (storeys/kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocks</td>
<td>103</td>
<td>0.0268</td>
</tr>
<tr>
<td>Thin-walled boxes</td>
<td>38</td>
<td>4.68</td>
</tr>
<tr>
<td>Unbraced frames</td>
<td>78</td>
<td>0.89</td>
</tr>
<tr>
<td>Braced frames</td>
<td>36</td>
<td>1.74</td>
</tr>
</tbody>
</table>

Figure 8 Unbraced frame with smaller deflection than braced frame [4]

Conclusions
The tallest realistic modular tower (78 storeys) uses an unbraced frame module. The lightest tower for its height uses a thin-walled box. However, all case study buildings fall below the tallest modular towers in this analysis, suggesting that higher towers may be possible. Note that this Ashby Chart is the first to consider actual structural forms.

Further research after this preliminary study will focus on the dynamics of tall modular buildings, in particular control and hence mitigation of excessive lateral displacements due to extreme events such as earthquakes or strong winds.

Table 2 Comparison of heights and modular tower weights

<table>
<thead>
<tr>
<th>Module type</th>
<th>Height (storeys)</th>
<th>Weight (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin-walled boxes</td>
<td>38</td>
<td>4.68</td>
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</tr>
</tbody>
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References

Contrasts: The tallest modular building is a single stack of perfectly connected steel modules was investigated – a modular tower. Figure 2 shows the loadings considered. Different generic module types were investigated, as shown in Figure 3; variations in manufacture were also considered.

Figure 3 Module types, solid block (a), thin-walled box (b), unbraced frame (c) and braced frame (d) [4]

Figure 4 Mini Sky City [6] 78 storeys

Figure 5 SOHO Apartments [7] 28 storeys

Figure 6 Victoria Hall [8] 9 storeys

Figure 7 Final Ashby Chart

Figure 8 Unbraced frame with smaller deflection than braced frame [4]

Victoria Hall and SOHO Apartments fall well within the clusters, with Mini Sky City on the edge of the data, having slightly lighter modules. Note, many of the existing buildings have separate lateral systems, unlike the modular towers in this analysis.

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