Utilisation of structural steel in buildings: supporting information

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This document contains supplementary information as described in the journal article “Utilisation of structural steel in construction”. It is divided into 3 sections:

- Section 1 contains results for each of the 23 buildings analysed as per section 4 of the journal article;
- Section 2 contains details on the design criteria included when calculating utilisation ratios, referenced in section 3.1 of the journal article;
- Section 3 contains the list of questions used when interviewing building designers, referenced in section 3.2 of the journal article.
SECTION 1: BUILDING DATA

This section details the results for each of the 23 buildings analysed. As agreed with the providers of the raw data, each building is identified only by a number, with the following information provided:

- Building type;
- Number of beam data obtained and number analysed;
- Table with summary of results by floor and overall;
- Graph of frequency of occurrence against utilisation ratio for each floor and overall;
- Plot of beam layout on each floor analysed showing utilisation ratio of each beam;
- Graph of frequency of occurrence against utilisation ratio for the columns in the building.

For all buildings it was possible to provide the first four items. However limitations in the data resulted in three categories of building for the remaining two items:

- For 17 buildings over 70% of the beams on each floor could be plotted, and once this level was reached the floor was deemed finished, as patterns were clear. Where necessary to complete the floor geometry, and so aid comprehension of the data, omitted beams were added in manually (coloured grey). Column locations were also added manually for this reason.
- For 6 buildings (#s 8, 9, 11, 16, 17, 21) there was insufficient information on beam layout to produce plots;
- For 1 building (# 10) there was insufficient information to produce a graph of column data.

For graphs, utilisation ratios are groups into bands of 10% to aid clarity; these bands are inclusive of the identifying upper bound, for example the data point at 0.2 includes U/Rs from 0.11 to 0.20.

For all plots of beam utilisation ratio per floor the legend below is used:
Building #1
Type: office
147 of 186 beams analysed (79%)

Table 1: summary of results by floor for building #1

| Level       | No. beams | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|-------------|-----------|-----------------------|----------|------------------|-------------|
|             | analysed  |                       |          |                  | No. | %    |
| Roof        | 15        | 3%                    | 0.23     | 0.34             | -  | -    |
| Plant room  | 54        | 55%                   | 0.49     | 0.65             | 35 | 65%  |
| 1st floor   | 52        | 42%                   | 0.39     | 0.57             | 30 | 58%  |
| TOTAL       | 147       | 100%                  | 0.36     | 0.43             | 98 | 66%  |

Figure 1: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #1
1st floor

Figure 2: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

Plant level

Figure 3: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

**Engineer's comments**

A proportion of beams governed by construction loading scenario, otherwise a standard building. A spot-check of beam sizes did not reveal any further rationalisation by fabricator. Robustness was not a governing criterion.
Columns
50 of 52 columns analysed (96%)
Average U/R: 0.31

Figure 4: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #1
Building #2
Type: hospital
779 of 802 beams analysed (97%)

Table 2: summary of results by floor for building #2

| Level    | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams|
|----------|--------------------|-----------------------|----------|-------------------|-------------|
|          |                    |                       |          |                   | No.  | %   |
| 2nd floor| 236                | 30%                   | 0.57     | 0.69              | 215  | 91% |
| 1st floor| 327                | 50%                   | 0.70     | 0.73              | 272  | 83% |
| Other    | 216                | 20%                   | 0.42     | 0.52              | -    | -   |
| TOTAL    | 779                | 100%                  | 0.58     | 0.68              | 532  | 68% |

Figure 5: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #2

Only one foundation drawing was available to base the below plots on – therefore column locations have been inferred and ‘missing’ beams added according to engineering intuition.
1\textsuperscript{st} floor

Figure 6: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

2\textsuperscript{nd} floor

Figure 7: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

**Engineer’s comments:**
No special vibration or other requirements.
Columns
147 of 156 columns analysed (94%)
Average U/R: 0.60

Figure 8: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #2
Building #3
Type: school
103 of 106 beams analysed (97%)

Table 3: summary of results by floor for building #3

| Level       | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|-------------|---------------------|-----------------------|----------|-------------------|-------------|
|             |                     |                       |          |                   | No. | %    |
| Roof        | 8                   | 32%                   | 0.35     | 0.63              | 8   | 100% |
| Plant Roof  | 26                  | 24%                   | 0.22     | 0.44              | 26  | 100% |
| 1st Floor   | 26                  | 20%                   | 0.22     | 0.53              | 26  | 100% |
| Other       | 43                  | 24%                   | 0.27     | 0.19              | -   | -    |
| TOTAL       | 103                 | 100%                  | 0.25     | 0.47              | 93  | 90%  |

Figure 9: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #3
Figure 10: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

Plant roof

Figure 11: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)
Engineer’s comments
Design deflection governed primarily; robustness not an issue.
Columns
30 of 30 columns analysed (100%)
Average U/R: 0.12

Figure 13: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #3
Building #4
Type: school
62 of 62 beams analysed (100%)

Table 4: summary of results by floor for building #4

| Level   | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|---------|--------------------|-----------------------|----------|-------------------|-------------|
| Roof    | 29                 | 78%                   | 0.22     | 0.75              | 29 100%     |
| 1st floor | 22              | 18%                   | 0.16     | 0.23              | 22 100%     |
| Other   | 11                 | 4%                    | 0.06     | 0.05              | - -         |
| TOTAL   | 62                 | 100%                  | 0.17     | 0.62              | 62 100%     |

Figure 14: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #4

1st floor

Figure 15: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)
Roof

![Roof Diagram]

Figure 16: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

**Engineer’s comments**
Design deflection governed primarily; robustness not an issue.

**Columns**
21 of 21 columns analysed (100%)
Average U/R: 0.13

![Frequency of Occurrence Graph]

Figure 17: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #4
Building #5
Type: office
21 of 21 beams analysed (100%)

Table 5: summary of results by floor for building #5

| Level   | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|---------|--------------------|-----------------------|----------|-------------------|-------------|
| Roof    | 21                 | 100%                  | 0.44     | 0.41              | -           |

Figure 18: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #5

Roof

Figure 19: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)
Engineer’s comments
The applied loads were reduced late in the project programme – too late to redesign, which resulted in spare capacity in places. Deflection governed most elements’ design.

Columns
15 of 15 columns analysed (100%)
Average U/R: 0.64

Figure 20: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #5
Building #6
Type: office & education
700 of 1194 beams analysed (59%)

Table 6: summary of results by floor for building #6

| Level   | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|---------|--------------------|-----------------------|----------|-------------------|-------------|
| Roof    | 197                | 19%                   | 0.12     | 0.22              | 139 71%     |
| 2nd floor | 229              | 28%                   | 0.11     | 0.27              | 195 85%     |
| 1st floor | 197              | 34%                   | 0.20     | 0.30              | 160 81%     |
| Other   | 77                 | 19%                   | 0.17     | 0.16              | - -         |
| TOTAL   | 700                | 100%                  | 0.15     | 0.25              | 541 77%     |

Figure 21: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #6

1st floor

Figure 22: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)
Figure 23: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

Engineer’s comments
Computer model used mainly for stability and column design purposes – may explain why so many beams omitted from analysis. Design around edges governed either by vibration or by minimum sizes for façade supporting steelwork (to facilitate faster construction).
Columns
75 of 75 columns analysed (100%)
Average U/R: 0.42

Figure 25: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #6
Building #7
Type: school
766 of 908 beams analysed (84%)

Table 7: summary of results by floor for building #7

| Level       | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams No. | %  |
|-------------|---------------------|-----------------------|----------|-------------------|-----------------|----|
| Top Roof    | 125                 | 8%                    | 0.17     | 0.25              | 125             | 100%|
| Roof        | 196                 | 23%                   | 0.28     | 0.39              | 158             | 81% |
| 3rd floor   | 114                 | 20%                   | 0.42     | 0.45              | 89              | 78% |
| 2nd floor   | 129                 | 21%                   | 0.44     | 0.54              | 118             | 91% |
| 1st floor   | 176                 | 26%                   | 0.40     | 0.53              | 150             | 86% |
| Other       | 26                  | 2%                    | 0.21     | 0.14              | -               | -   |
| Total       | 766                 | 100%                  | 0.33     | 0.45              | 474             | 62% |

Figure 26: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #7
Figure 27: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

2nd floor

Figure 28: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)
3rd floor

Figure 29: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

Roof

Figure 30: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

There was not sufficient information to plot the Top Roof level.

Engineer’s comments
Vibration governed in some places but mainly stress and deflection governed.
Columns
103 of 113 columns analysed (91%)
Average U/R: 0.47

Figure 31: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #7
Building #8

Type: office
375 of 519 beams analysed (72%)

Table 8: summary of results by floor for building #8

| Level     | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|-----------|--------------------|-----------------------|----------|-------------------|-------------|
| Roof      | 101                | 23%                   | 0.23     | 0.30              | 83          | 82%         |
| 4th floor | 70                 | 18%                   | 0.34     | 0.43              | 63          | 90%         |
| 3rd floor | 67                 | 16%                   | 0.33     | 0.41              | 67          | 100%        |
| 2nd floor | 70                 | 18%                   | 0.34     | 0.43              | 63          | 90%         |
| 1st floor | 66                 | 18%                   | 0.35     | 0.44              | 57          | 86%         |
| TOTAL     | 375                | 100%                  | 0.31     | 0.39              | 312         | 83%         |

Figure 32: graph of frequency of occurrence against utilisation ratio for beams by floor and in total for building #8

No data on beam layout was available for this building; therefore floor plots could not be created.

Engineer’s comments
Most of the beams not analysed in model were specially-fabricated beams. These beams are expected to have high U/R.
Columns
38 of 40 columns analysed (95%)
Average U/R: 0.72

Figure 33: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #8
Building #9
Type: office
512 of 606 beams analysed (84%)

Table 9: summary of results by floor for building #9

| Level     | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|-----------|--------------------|-----------------------|----------|-------------------|-------------|
| Roof      | 131                | 27%                   | 0.34     | 0.46              | 80          | 61%         |
| 3rd floor | 112                | 24%                   | 0.44     | 0.55              | 68          | 61%         |
| 2nd floor | 115                | 25%                   | 0.43     | 0.54              | 70          | 61%         |
| 1st floor | 111                | 22%                   | 0.38     | 0.47              | 64          | 58%         |
| Other     | 43                 | 3%                    | 0.09     | 0.19              | -           | -           |
| TOTAL     | 512                | 100%                  | 0.37     | 0.50              | 294         | 57%         |

![Graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #9](image)

Figure 34: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #9

No data on beam layout was available for this building; therefore floor plots could not be created.

Engineer's comments
Vibration was a governing criterion in a small area. Many of the beams not analysed were specially-fabricated beams, expected to have high U/R.
Columns
56 of 59 columns analysed (95%)
Average U/R: 0.60

Figure 35: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #9
Building #10
Type: office
35 of 48 beams analysed (73%)

Table 10: summary of results by floor for building #10

| Level  | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams No. | %     |
|--------|--------------------|-----------------------|----------|-------------------|----------------|-------|
| Roof   | 35                 | 100%                  | 0.90     | 0.96              | 3              | 100   |

Figure 36: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #10
**Figure 37**: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

**Engineer’s comments:**
Deflections governed design. Not surprised that had high U/R as had time to design thoroughly and no late changes were made.

*Insufficient information was available about the columns in this building to allow analysis.*
Building #11
Type: school
379 of 503 beams analysed (75%)

Table 11: summary of results by floor for building #11

| Level   | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|---------|--------------------|----------------------|----------|------------------|-------------|
| Roof    | 98                 | 24%                  | 0.66     | 0.70             | 74          |
| 2nd floor | 143               | 39%                  | 0.64     | 0.68             | 108         |
| 1st floor | 138               | 24%                  | 0.63     | 0.68             | 106         |
| TOTAL   | 379                | 100%                 | 0.64     | 0.68             | 269         |

Figure 38: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #11

*Insufficient data on beam layout were available for this building to create layout plots.*

**Engineer’s comments**
Steelwork was rationalised to enable cheaper procurement – fabricator further rationalised the design also.
Columns
55 of 109 columns analysed (50%)
Average U/R: 0.69

Figure 39: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #11
Building #12
Type: school
526 of 578 beams analysed (91%)

Table 12: summary of results by floor for building #12

| Level     | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams No. | %   |
|-----------|--------------------|-----------------------|----------|-------------------|-----------------|-----|
| 2nd floor | 241                | 42%                   | 0.41     | 0.57              | 178             | 74% |
| 1st floor | 201                | 42%                   | 0.61     | 0.69              | 93              | 46% |
| Other     | 84                 | 16%                   | 0.30     | 0.44              | -               | -   |
| TOTAL     | 526                | 100%                  | 0.47     | 0.60              | 339             | 64% |

Figure 40: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #12
Engineer’s comments
Steelwork was rationalised to enable cheaper procurement – fabricator further rationalised the design also. Regular column grid prevented by client desire to provide minimum required area (lower heating costs) and to minimise cladding cost.
Columns
100 of 108 columns analysed (93%)
Average U/R: 0.49

Figure 43: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #12
Building #13
Type: school
311 of 372 beams analysed (84%)

Table 13: summary of results by floor for building #13

| Level    | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|----------|--------------------|-----------------------|----------|------------------|-------------|
| 1st floor| 86                 | 18%                   | 0.47     | 0.64             | 79          | 92%         |
| Other    | 225                | 82%                   | 0.36     | 0.46             | -           | -           |
| TOTAL    | 311                | 100%                  | 0.39     | 0.49             | 230         | 75%         |

This building was composed of many different levels with less than 20 beams on each, which did not merit plotting individually, hence only the first floor is examined in detail.

Figure 44: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #13
1st floor

Figure 45: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

**Engineer’s comments**
Steelwork was rationalised to enable cheaper procurement – fabricator further rationalised the design also.

**Columns**
64 of 74 columns analysed (86%)
Average U/R: 0.52

Figure 46: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #13
Building #14

Type: school

751 of 760 beams analysed (99%)

Table 14: summary of results by floor for building #14

| Level    | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams No. | %   |
|----------|--------------------|-----------------------|----------|-------------------|-----------------|-----|
| Roof     | 86                 | 11%                   | 0.24     | 0.42              | 65              | 79% |
| 2nd floor| 330                | 52%                   | 0.23     | 0.33              | 275             | 84% |
| 1st floor| 322                | 35%                   | 0.29     | 0.44              | 241             | 75% |
| Other    | 13                 | 2%                    | 0.23     | 0.41              | -               | -   |
| TOTAL    | 751                | 100%                  | 0.26     | 0.38              | 585             | 78% |

Figure 47: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #14
1st floor

Figure 48: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

2nd floor

Figure 49: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

Roof

Figure 50: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

Roof column layout drawings were not available so Figure 53 was plotted using engineering intuition based on the other two floors.
Engineer’s comments
Many beams governed by loading during construction. Increasing mass to take this load was deemed the cheapest option, as other solutions required more labour on site. A small number of beams were governed by vibration concerns.

Columns
166 of 168 columns analysed (99%)
Average U/R: 0.54

Figure 51: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #14
**Building #15**

Type: mixed-use residential and retail

1447 of 2230 beams analysed (65%)

Table 15: summary of results by floor for building #15

| Level          | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|----------------|--------------------|-----------------------|----------|-------------------|-------------|
| Roofs          | 75                 | 4%                    | 0.17     | 0.31              | 59          |
| 7th – 11th floor* | 64                 | 3%                    | 0.10     | 0.15              | 55          |
| 6th floor      | 105                | 7%                    | 0.19     | 0.40              | 87          |
| 3rd - 5th floor* | 154                | 8%                    | 0.16     | 0.35              | 129         |
| 2nd floor      | 154                | 8%                    | 0.16     | 0.35              | 100         |
| 1st floor      | 127                | 9%                    | 0.24     | 0.46              | 126         |
| Ground floor   | 115                | 17%                   | 0.29     | 0.48              | 82          |
| Basement       | 89                 | 16%                   | 0.32     | 0.46              | 77          |
| **TOTAL**      | **1447**           | **100%**              | **0.18** | **0.37**          | **1073**    |

*Floors 3-5 have very similar beam numbers, sections, utilisations and layouts so the data for just one of these floors is presented in Table 15, similarly for floors 7-11.

Figure 52: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #15
Figure 53: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

Ground floor

Figure 54: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)
1st floor

Figure 55: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

2nd floor

Figure 56: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)
3rd – 5th floors

Figure 57: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

6th floor

Figure 58: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)
**7th – 11th floors**

![Diagram of 7th to 11th floors]

Figure 59: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

**Roof**

![Diagram of Roof]

Figure 60: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

**Engineer’s comments**

Complex procurement involved fabricator twice ‘transposing’ sections between UK, Russian and Chinese steel catalogues (for cost reasons), choosing heavier section each time ‘to be conservative’. Design was originally stress-governed however.
Columns
68 of 215 columns analysed (32%)
Average U/R: 0.62

Figure 61: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #15
Building #16
Type: mixed use residential
364 of 536 beams analysed (68%)

Table 16: summary of results by floor for building #16

| Level  | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|--------|--------------------|-----------------------|----------|------------------|--------------|
| Roof   | 30                 | 12%                   | 0.33     | 0.51             | 27           |
| 5th floor | 72               | 19%                   | 0.23     | 0.49             | 66           |
| 4th floor | 72               | 19%                   | 0.22     | 0.47             | 66           |
| 3rd floor | 73               | 20%                   | 0.24     | 0.49             | 67           |
| 2nd floor | 67               | 15%                   | 0.19     | 0.43             | 61           |
| 1st floor | 50               | 16%                   | 0.23     | 0.39             | 47           |
| TOTAL  | 364                | 100%                  | 0.23     | 0.46             | 345          |

Figure 62: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #15

Insufficient data on beam layout were available for this building to create layout plots.

Engineer’s comments
Complex procurement involved fabricator twice ‘transposing’ sections between UK, Russian and Chinese steel catalogues, adding weight each time ‘to be conservative’.
Columns
61 of 215 columns analysed (28%)
Average U/R: 0.57

Figure 63: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #16
Building #17
Type: mixed-use
631 of 947 beams analysed (67%)

Table 17: summary of results by floor for building #17

| Level      | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|------------|--------------------|-----------------------|----------|-------------------|-------------|
| 8th floor  | 69                 | 10%                   | 0.50     | 0.68              | 52          |
| 7th floor  | 67                 | 10%                   | 0.54     | 0.68              | 52          |
| 6th floor  | 67                 | 10%                   | 0.54     | 0.68              | 52          |
| 5th floor  | 67                 | 10%                   | 0.54     | 0.68              | 52          |
| 4th floor  | 67                 | 10%                   | 0.54     | 0.68              | 52          |
| 3rd floor  | 67                 | 10%                   | 0.54     | 0.68              | 52          |
| 2nd floor  | 105                | 26%                   | 0.65     | 0.77              | 84          |
| 1st floor  | 67                 | 10%                   | 0.50     | 0.63              | 50          |
| Others     | 55                 | 4%                    | 0.19     | 0.25              | -           |
| TOTALS     | 631                | 100%                  | 0.52     | 0.70              | 514         |

Figure 64: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #17

No data on beam layout was available for this building; therefore floor plots could not be created.

Engineer's comments
Vibration governed much of design; this combined with desire to minimise structural depth (to reduce cladding costs) lead to a heavy solution.
Columns
65 of 164 columns analysed (40%)
Average U/R: 0.60

Figure 65: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #17
Building #18
Type: office
200 of 316 beams analysed (63%)

Data was only obtained for floors 2 and 10 of this 11-storey building.

Table 18: summary of results by floor for building #18

| Level     | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams No. | %   |
|-----------|--------------------|-----------------------|----------|-------------------|----------------|-----|
| 10th floor| 69                 | 36%                   | 0.34     | 0.57              | 67             | 97% |
| 2nd floor | 131                | 64%                   | 0.64     | 0.71              | 127            | 97% |
| TOTAL     | 200                | 100%                  | 0.54     | 0.66              | 194            | 97% |

Figure 66: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #18
2nd floor

Figure 67: plot of
2\textsuperscript{nd} floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

**10\textsuperscript{th} floor**

![Diagram of 10\textsuperscript{th} floor]

Figure 68: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

**Engineer’s comments**

Vibration governed much of design. Desire to reduce cladding costs through minimum structural depth sections lead to use of heavy sections.
Columns
57 of 57 columns analysed (100%)
Average U/R: 0.12

Figure 69: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #18
Building #19
Type: school
499 of 527 beams analysed (95%)

Table 19: summary of results by floor for building #19

| Level    | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|----------|--------------------|-----------------------|----------|-------------------|-------------|
| Roof     | 30                 | 4%                    | 0.50     | 0.60              | -           |
| 2nd floor| 240                | 54%                   | 0.30     | 0.37              | 176         |
| 1st floor| 229                | 42%                   | 0.40     | 0.48              | 192         |
| TOTAL    | 499                | 100%                  | 0.36     | 0.43              | 355         |

Figure 70: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #19
1st floor

Figure 71: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

2nd floor

Figure 72: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

There was insufficient information to construct a plot for the roof level.

Engineer’s comments
Primarily deflection governed design.
Columns
150 of 151 columns analysed (99%)
Average U/R: 0.49

Figure 73: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #19
Building #20
Type: school
314 of 322 beams analysed (98%)

Table 20: summary of results by floor for building #20

| Level      | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|------------|--------------------|-----------------------|----------|-------------------|-------------|
| 2nd floor  | 81                 | 30%                   | 0.26     | 0.54              | 105         |
| 1st floor  | 119                | 55%                   | 0.61     | 0.81              | 62          |
| Other      | 114                | 15%                   | 0.09     | 0.35              | -           |
| TOTAL      | 314                | 100%                  | 0.33     | 0.66              | 233         |

Figure 74: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #20

1st floor

Figure 75: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)
2nd floor

Figure 76: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

Engineer's comments
Vibration considerations governed design of many areas.

Columns
95 of 96 columns analysed (99%)
Average U/R: 0.35

Figure 77: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #20
Building #21
Type: residential
71 of 73 beams analysed (97%)

Only data for one floor was available for this building, and no information about beam layout.

Table 21: summary of results by floor for building #21

| Level    | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|----------|--------------------|-----------------------|----------|------------------|-------------|
| 1st floor| 71                 | 100%                  | 0.55     | 0.61             | 70          | 99          |

Figure 78: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #21

Engineer’s comments:
Beam depth specified by architecture – could not even be smaller – therefore very limited range to select from. Vibration governed in some areas.
Columns

213 of 213 columns analysed (100%) – data available for all columns in building
Average U/R: 0.65

![Graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #21](image)

Figure 79: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #21
Building #22
Type: school
605 of 613 beams analysed (99%)

Table 22: summary of results by floor for building #22

| Level    | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams No. | %   |
|----------|--------------------|-----------------------|----------|-------------------|-----------------|-----|
| Roof     | 150                | 24%                   | 0.36     | 0.45              | 119             | 82% |
| 2nd floor| 208                | 41%                   | 0.57     | 0.66              | 174             | 91% |
| 1st floor| 212                | 33%                   | 0.55     | 0.64              | 170             | 87% |
| Other    | 35                 | 2%                    | 0.53     | 0.38              | -               | -   |
| TOTALS   | 605                | 100%                  | 0.47     | 0.63              | 471             | 78% |

Figure 80: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #22
1st floor

Figure 81: plot of floor showing beams coloured according to utilisation ratio (as per legend 1, pg. 1)

2nd floor

Figure 82: plot of floor showing beams coloured according to utilisation ratio (as per legend 1, pg. 1)
Roof

Figure 83: plot of floor showing beams coloured according to utilisation ratio (as per legend 1, pg. 1)

Engineer’s comments
Smaller beams oversized to allow faster assembly. Repetition in section sizes encouraged to facilitate faster construction.

Columns
111 of 118 columns analysed (94%)
Average U/R: 0.55

Figure 84: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #22
Building #23
Type: school
528 of 558 beams analysed (95%)

Table 23: summary of results by floor for building #23

| Level   | No. beams analysed | % of total steel mass | Avg. U/R | Weighted avg. U/R | Top 5 Beams |
|---------|--------------------|-----------------------|----------|-------------------|-------------|
| Roof    | 199                | 36%                   | 0.34     | 0.47              | 173         | 87%         |
| 1st floor| 209                | 46%                   | 0.49     | 0.66              | 174         | 83%         |
| Other   | 124                | 18%                   | 0.10     | 0.16              | -           | -           |
| TOTAL   | 532                | 100%                  | 0.35     | 0.50              | 464         | 87%         |

Figure 85: graph of frequency of occurrence against utilisation ratio for beams by floor and overall for building #23

The presence of gridlines with identical names but non-identical coordinates required that the figures below were assembled manually in places, using engineering intuition to assess where beams were located.
1st floor

Figure 86: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

Roof

Figure 87: plot of floor showing beams coloured according to utilisation ratio (as per legend pg. S2)

Engineer’s comment
Beams in SE portion governed by vibration, beams along SW governed by stability concerns.
Repetition of section sizes encouraged to facilitate faster construction.
Columns
98 of 98 columns analysed (100%)
Average U/R: 0.60

Figure 88: graph of frequency of occurrence against utilisation ratio for columns by floor and overall for building #23
SECTION 2: DESIGN CRITERIA

This section contains details of the design criteria used to evaluate the governing utilisation ratio for each beam and column in each building.

1. Moment capacity
   - About major axis
   - About minor axis
   - Reduced moment capacity – e.g. at holes, near support
     - About major axis
     - About minor axis

2. Shear capacity
   - In direction of minor axis
   - In direction of major axis

3. Axial capacity

4. Buckling*
   - Lateral torsional buckling
   - Strut buckling at various sections

5. Combined axial and moment buckling
   - About major axis
   - About minor axis

6. Deflection
   - Due to dead load
   - Due to imposed load
   - Due to all loads

Other criteria, such as torsion and combined shear and torsion, were included in U/R calculation when specified as governing by calculations or by designer, but otherwise were omitted.

All checks done to worst loading scenario.

*Shear web buckling was checked on a pass/fail basis – i.e. not used to calculated U/R.
SECTION 3: LIST OF QUESTIONS FOR INTERVIEWS
The below template was used when interviewing design engineers. Further unscripted questions were asked to gain more information as necessary.

Utilisation study: questions for interviews

Interviewee: Building name (#):
Email: Emailed in advance on: / /

1. What do you think the average U/R for the building is?

2. At what stage was job handed over? I.e. what stage was model/calc at?
   a. Was model handed to fabricator? Any idea if tonnage up or down for construction?

3. This study included moment, shear, axial, buckling, combined cases and deflection;
   a. Are there any other design cases that governed? If so where?
      i. Vibration
      ii. Construction loads
      iii. Section depth – if so how onerous?
      iv. Connections
   b. Were any design limits more onerous than included in model?
      i. deflection limits

4. How was robustness (disproportionate collapse) accounted for in design and how do you think this would impact on utilisation?
   a. Were any beam sizes changed for robustness specifically?

5. Anything else that will impact my study?