Bickerdike Allen Partners

Review report on Concrete Testing
Shakespeare, Cromwell & Lauderdale Towers
The Barbican, London

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Prepared for: City of London Corporation

0 Summary

0.1 Following the identification of small pieces of concrete that were spalled (ie split from the face of the concrete) but still retained on the external surface of the concrete of Shakespeare Tower, a 100% visual and hammer tap survey by abseilers was commissioned to identify other similar potential safety hazards on all 3 tower blocks.

0.2 Every panel was also spot checked for the thickness of the concrete cover to the reinforcement, and a selection of 90 panels per block were tested on their outer external surfaces to assess them for actual and potential deterioration.

0.3 The results obtained showed the reinforced concrete to be in very good condition for its age with only minor occurrences of normal types of defects. These have no structural implications but will require some intervention to prevent local deterioration in the future and the risk of detachment of further pieces of concrete.

1 Introduction

1.1 The City of London Corporation (the Corporation) has instructed Bickerdike Allen Partners (BAP) to review and comment on the testing and results obtained from some of the concrete in the three tower blocks that form part of the Barbican Estate. Any survey work carried out by BAP in connection with this commission is limited to the scope of that instruction

1.2 Following the identification of the spalling / detachment of a number of a number of small but not insignificant pieces of concrete from Shakespeare Tower, a survey of the safety of the external concrete surfaces that were likely to be at risk of generating further such occurrences was commissioned by the Corporation.

1.3 The safety survey and testing were carried out by specialist testers using abseil access following a tender process that was awarded on the basis of competence as well as price. A key element of the tender was the inclusion in the report of an interpretation of the test results obtained in terms of their significance to the durability and longevity of the tower structures, and the need for and detailed nature of any repairs required. BAP were also instructed to advise on the selection and evaluation of the bids for the work.

1.4 This report reviews the testing carried out by the contractor Structural Renovations Ltd and the interpretation of the results as offered by their specialist testing subcontractor Martech Technical Services Ltd. The full reports of the testing are available via the Corporation.

2 The need for the survey

2.1 In reinforced concrete structures, corrosion of embedded reinforcement is initially inhibited by the alkalinity of the concrete. This alkalinity is reduced gradually over time by the effects of exposure to carbon dioxide in the atmosphere, a process known as carbonation.

In good quality concrete, carbonation is likely to begin to put the steel reinforcement at risk after a period of 40-60 years, or less if there is low cover of concrete (ie the thickness of concrete) over the steel. In poor quality concrete (which can occur for several reasons) or if it contains calcium chloride (which in the 1960's and 70's may have been used to accelerate the setting of concrete) the risk of corrosion can be much higher.

2.2 The tower blocks in the Barbican were built at different times between the mid 1960's to the mid-1970's. The designs appear very similar and the structural design and concrete design were probably also essentially the same.

2.3 Parts of the concrete construction are made from precast concrete units but the majority of the concrete was cast in situ.

2.4 The concrete in the Barbican is now typically 40 – 50 years old and is approaching the age at which even good quality concrete may start to show some problems.

2.5 The detachment of the concrete pieces is an indication of possible potential problems, so there was a need to establish as quickly as possible the risk of further detachments, and the need for any intervention to prevent any more from developing in the future.

2.6 No information is available on the concrete mix as originally specified, and the cover to the steel although specified to be unusually high for the time may vary significantly from the specified thickness. The purpose of the survey was therefore:-

i) To carry out an overall visual and hammer tapping inspection to identify areas of change or deterioration.
ii) To carry out sample checks on cover to the reinforcement
iii) To carry out tests on concrete samples to confirm whether it posed any additional risks.

3 The survey

3.1 The survey was undertaken in two distinct parts –

i) The safety survey where all the external concrete surfaces over public areas were visually examined by an appropriately experienced abseiler, the cover to the reinforcement was assessed and the surfaces were tapped with a hammer to detect any loose concrete. Loose pieces were removed and safely brought down.

ii) A distributed survey of typical structural elements on every elevation of each tower involving some standard concrete tests to establish if there may be aspects of the concrete condition that require further investigation.

3.2 The distributed testing was carried out to act as an indicator of possible issues with the concrete, as a full survey would have taken an extremely long time to carry out and hence prohibitively expensive. Distributed testing of a sample of structural members is not truly random sampling but is sufficiently representative to give an indication if there are patterns of defects that occur in similar structural members.

3.3 The testing was not designed or intended to identify isolated one-off defects; from experience the visual survey will reveal one-off defects that need immediate attention.

3.4 The testing consisted of a number of standard concrete tests namely cover to reinforcement, depth of carbonation and cement content. Initially some tests to assess the corrosion of the reinforcement were carried out but the results did not suggest that there was any worthwhile data to be obtained so this was discontinued.

4 Results

4.1 The observations and measurements from the safety survey are shown in the elevation drawings which are attached in **Appendix A** to the paper copy of this report at size A1, however in the electronic copy these are not easily read at A3 size.

4.2 The detailed results are given in the contractors reports for each tower block and in the marked-up elevation drawings. The test results from the 90 test areas (30 per elevation) are summarised in Table 1 below.

4.3 The results for the distributed test areas are reported as follows:-

Table 1 Reported concrete test results

The Elements tests are illustrated in Figure 1.

Shakespeare Tower									
Element	**Depth of Cover** (mm)			**Depth of Carbonation** (mm)			**Chloride Content** (%) *		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Landing Beam	3	67	43	<5	15	7	0.08	0.29	0.18
Wall	0	>80	53	<5	>50#	13	0.17	0.33	0.23
Spandrel Panel	29	>100	60	<5	20	8	0.10	0.73	0.20
Balcony	7	>100	42	<5	15	7	0.13	0.26	0.17
Column	0	>100	55	<5	>70#	10	0.08	0.33	0.20
Round Column	45	>80	61	<5	10	4	0.14	0.26	0.19
Cromwell Tower									
Element	**Depth of Cover** (mm)			**Depth of Carbonation** (mm)			**Chloride Content** (%) *		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Landing Beam	8	80	47	<5	40	11	0.08	0.93	0.39
Wall	13	89	54	<5	25	13	0.09	0.36	0.19
Spandrel Panel	22	99	53	<5	10	5	0.08	0.59	0.26
Balcony	0	88	41	<5	20	8	0.10	0.25	0.15
Column	28	95	62	<5	70	11	0.09	0.30	0.18
Round Column	3	81	67	5	10	8	0.22	0.29	0.25
Lauderdale Tower									
Element	**Depth of Cover** (mm)			**Depth of Carbonation** (mm)			**Chloride Content** (%) *		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Landing Beam	6	83	38	<5	40	9	0.16	0.42	0.26
Wall	6	>100	56	<5	15	6	0.13	0.30	0.22
Spandrel Panel	15	80	54	<5	10	5	0.15	0.41	0.25
Balcony	10	82	43	<5	25	7	0.10	0.45	0.18
Column	17	84	60	<5	35	5	0.14	0.34	0.23
Round Column	78	90	84	<5	10	6	0.23	0.35	0.30

Notes # deep results recorded only at poorly compacted / honeycombed areas

*Chlorides expressed as % ions by mass of cement using a calculated mean cement content of

Shakespeare = 20.7%, (17.2% to 22.7%)
Cromwell = 19.4%, (18.8% to 22.3%)
Lauderdale = 20.2%, (13.7% to 26.7%)

Depth of cover

4.4 The minimum spot cover for each area is shown in Appendix A and few show values less than 20mm. The minimum values in Table 1 are very localised; where they are 0 they are exposed bar ends or where the steel is visible in honeycombed concrete. Unless associated with spalling of the concrete cover the low cover would usually relate to locally misplaced reinforcement where the next bar would be deeper into the concrete.

Depth of Carbonation

4.5 The test results show the depth of carbonation is typically less than 5mm in dense concrete. This is an extremely low value and suggests that the typical concrete was dense and very high quality.

4.6 The relationship between depth of carbonation and time is such that if it has taken 40 years to carbonate 5mm the next 5mm will take a further 120 years. Consequently other than at locations of extremely low cover there appears to be little risk of carbonation induced corrosion on the outer faces of the concrete. The accessible and non safety-critical inner faces have not been assessed and it would be prudent to carry out testing of these faces at some time.

Chloride content

4.7 The chloride contents are generally below the 0.4% by mass of cement which for 40 year old damp alkaline concrete is the level at which a low risk of corrosion becomes moderate.

4.8 There are some isolated results which were higher than this threshold level but none were indicating a high risk of corrosion or appeared to have defects that might be associated with this. In the absence of evidence of deterioration at these locations should be investigated further as soon as practicable to confirm the results, and to identify the source of the chloride contamination. Initially these could be from the balcony for ease of access.

4.9 The significance of the chloride content results depends to some extent on the cement content results. The cement content results for Lauderdale appear very variable but they are within a normal range for precast and in-situ concretes, both of which were sampled in this survey. Taking the mean of this range as representing all the concrete is not unreasonable for a first assessment and the indications from the chloride contents is that there is nothing that gives cause for immediate concern, especially when considered with the low depth of carbonation.

Half cell potential and Resistivity

4.10 Half Cell Testing and Resistivity tests were carried out at 9 or 10 locations on each block. In general all the results indicated a low probability of corrosion but at a few locations in each building results indicating a higher probability were obtained. These were all associated with small concrete spalls which confirms that some corrosion was occurring at these locations but also indicates that where conditions were right for corrosion it was already manifested by spalling so it may be inferred that it is not occurring elsewhere.

5 Remedial works

5.1 The results indicate that a relatively small number of repairs are needed and only a small proportion of those require a volume of repair materials, the majority are small holes, cracks or shallow spalls.

5.2 Where there are indications of corrosion of the steel reinforcement some corrosion inhibition treatment would be justified and the least intrusive of these are the migrating corrosion inhibitors (mci) or vapour phase corrosion inhibitors (vpi). Both are introduced close to the steel via a drilled hole.

5.3 The typically low depth of carbonation means there is no need for a general anti-carbonation coating.

5.4 The remedial works contractor should propose materials and methods of executing these works, which can then be independently reviewed.

6 Review of the test reports

6.1 Bickerdike Allen Partners have reviewed the test reports and prepared the above summaries based on them. In our opinion the analysis, interpretation and recommendations presented by the test contractor are reasonable from the data obtained.

6.2 In our opinion it is reasonable to base strategies for any remedial works and maintenance on the reports.

7 Further investigations

The following suggestions for further investigations are offered by Bickerdike Allen Partners as a starting point for the development of a full repair and maintenance programme. They are not intended to be a full or complete analysis of whatever might be necessary to ensure the long term integrity of the structures.

7.1 The concrete structures of the Barbican Estate are of an age where deterioration might be expected to start and susceptible locations should be identified early to optimise any intervention for repairs.

7.2 The top surfaces of the balcony panels have numerous minor defects including holes drilled for glass balustrade supports and steel exposed by surface spalls. These can be accessed from the balconies and a systematic record should be made of all such items so that a programme of repairs can be carried out.

7.3 Similarly the balcony-facing concrete in the outdoor concrete on the inside of the outer envelope, the apartment walls and the ceilings over the balconies should be systematically checked by methods similar to those use to inspect and test the external faces of the envelope.

7.4 Even if these tests indicate there is little of current concern the results obtained will provide a baseline for further test results from future surveys that must be implemented to ensure the long term integrity of the structures.

7.5 Consideration should be given to carrying out a programme of safety checks on the external surfaces of the medium rise structures as these will be affected by the same physical and chemical deterioration processes as the high rise blocks and concrete falling from the 4th floor can be as injurious as that from the 34th floor.

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Figure 1
Elements of the buildings


Columns
Wall
Spandrel Panel


Landing Beam
Wall
Balcony

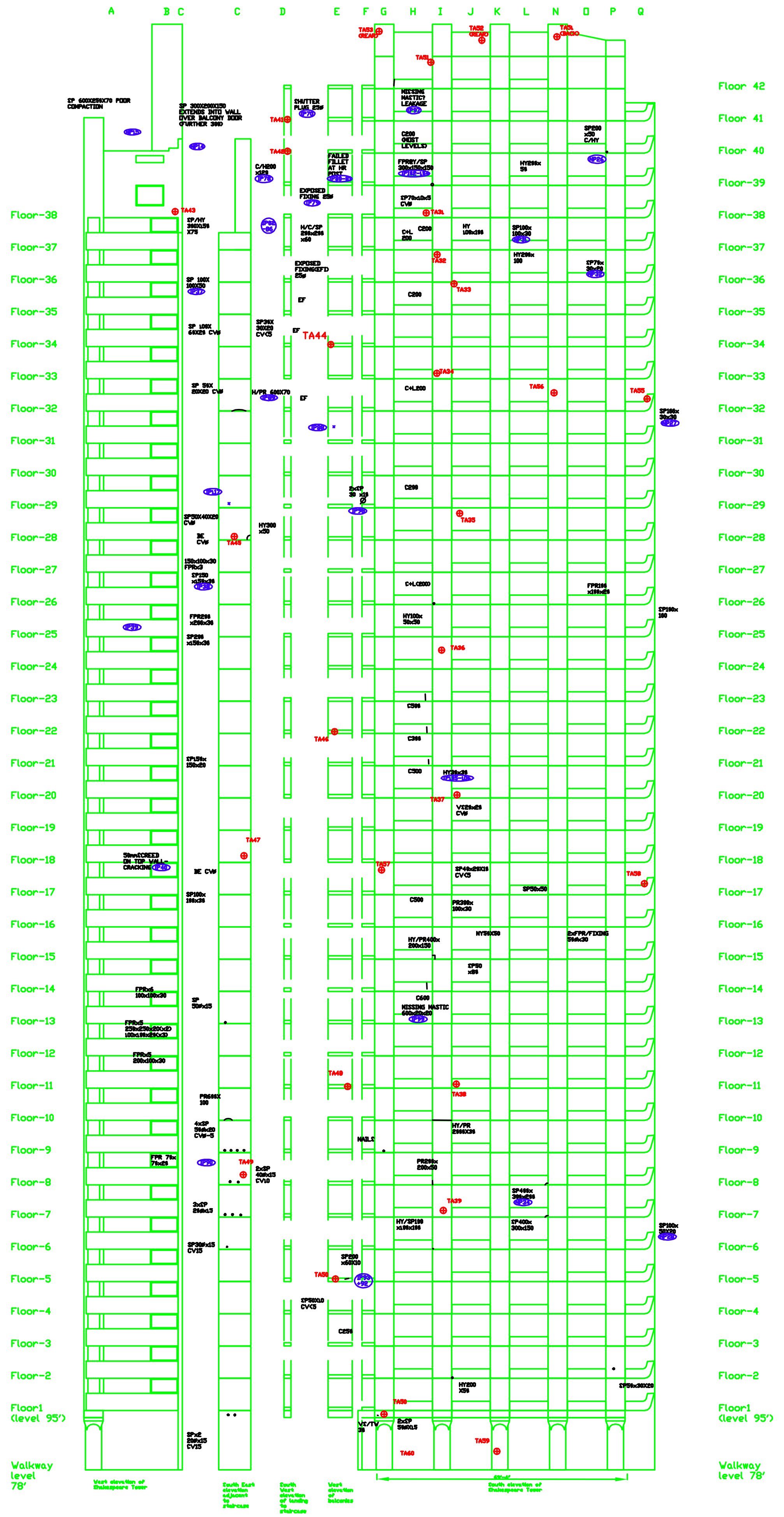

Round Columns

APPENDIX A

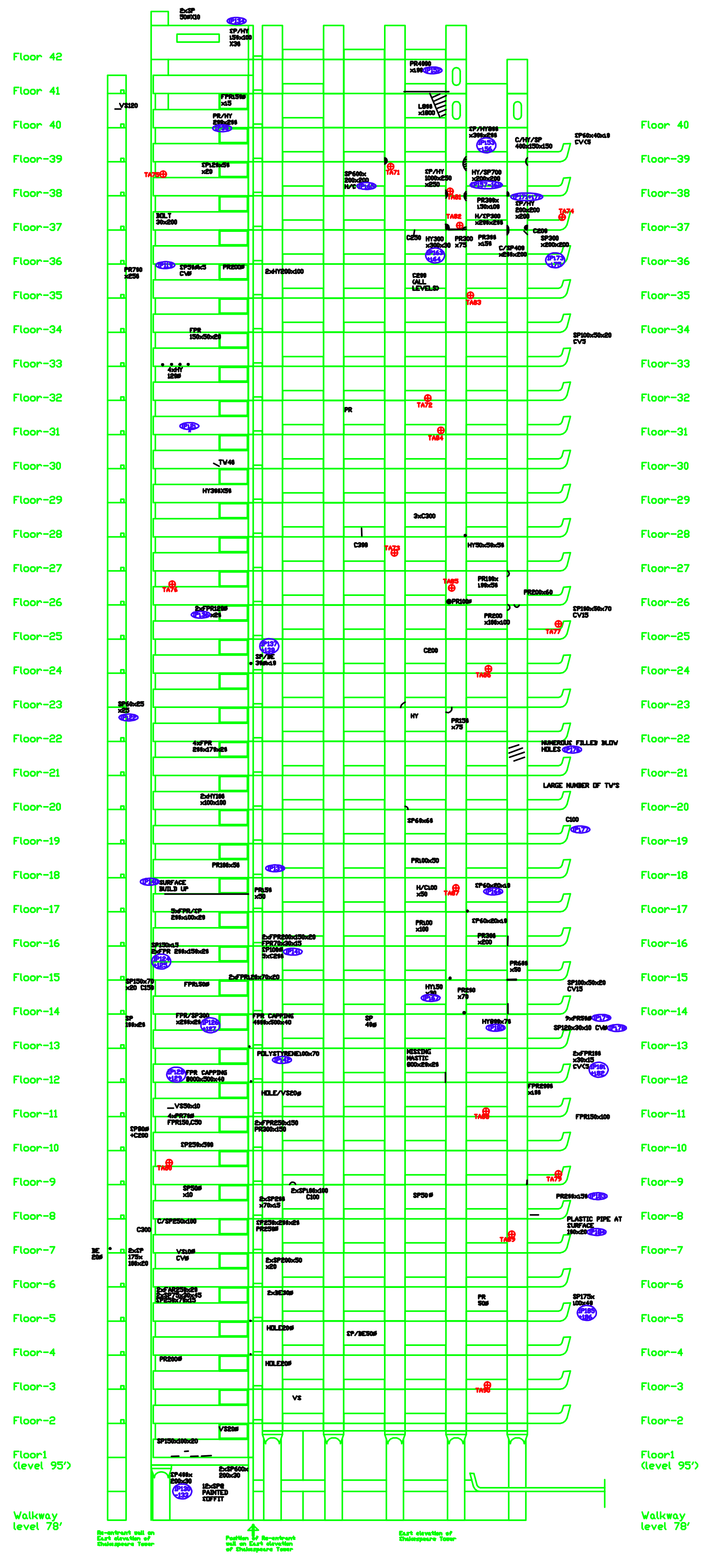
SURVEY RESULTS FOR SHAKESPEARE, CROMWELL & LAUDERDALE TOWERS

LEGEND

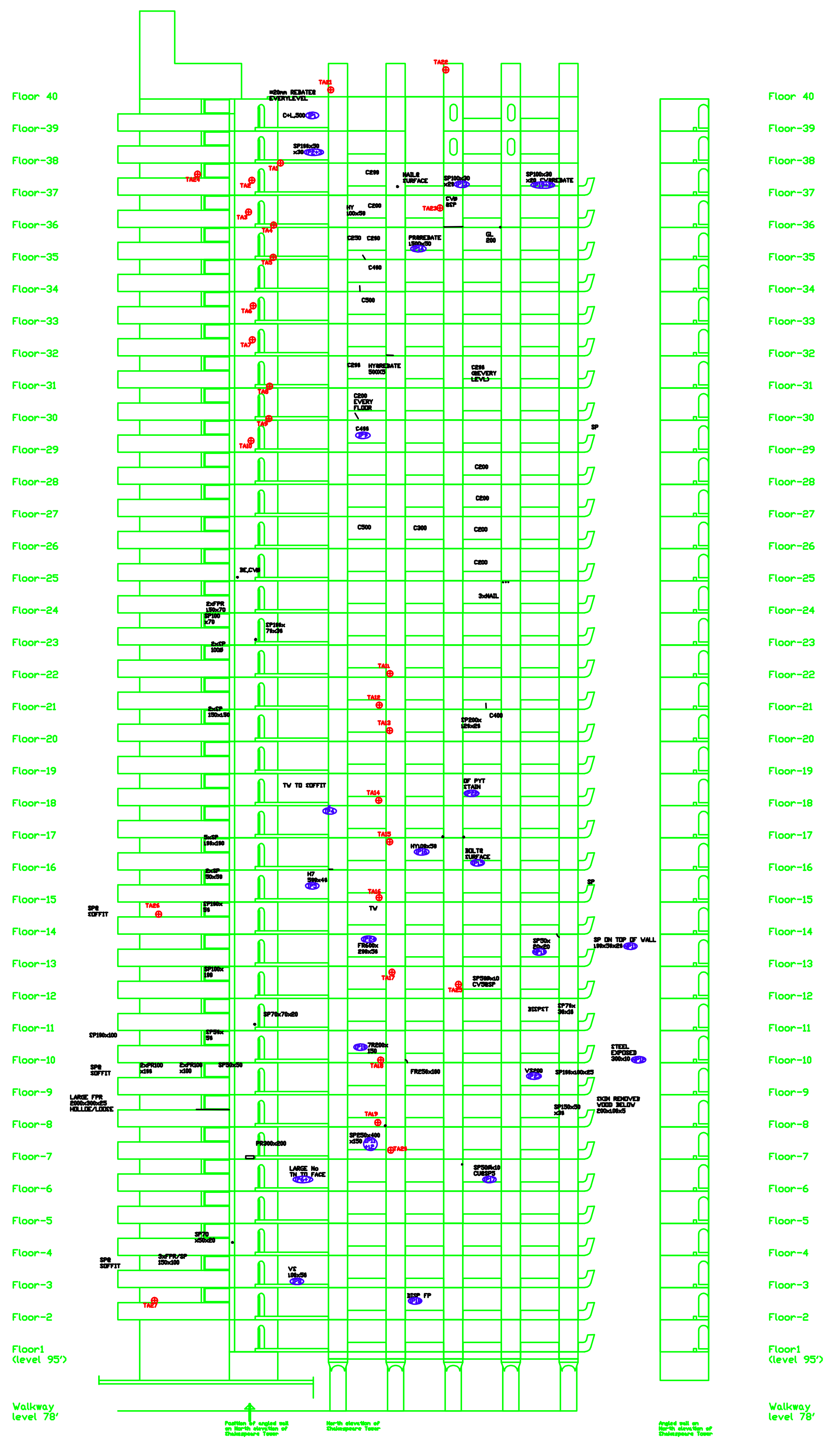
TA	Test Area Location and Reference
⊕ S	Sample Location and Reference
CV	Depth of Cover (mm)
BWK	Brickwork
CB	Depth of Carbonation (mm)
C+P	Clean and Passive Steel
SP	Spall
PR	Previous Repair
RS	Rust Spot/Stain
PY	Pyrite
BE	Bar End
B/O	Breakout to Expose Reinforcement
c	Crack
VS	Visible Steel
45	Rebar Location and Depth of Cover (mm)
HY	Honeycombing / poor compaction
SSC	Slight Surface Corrosion
SC	Surface Corrosion
H	Hollow



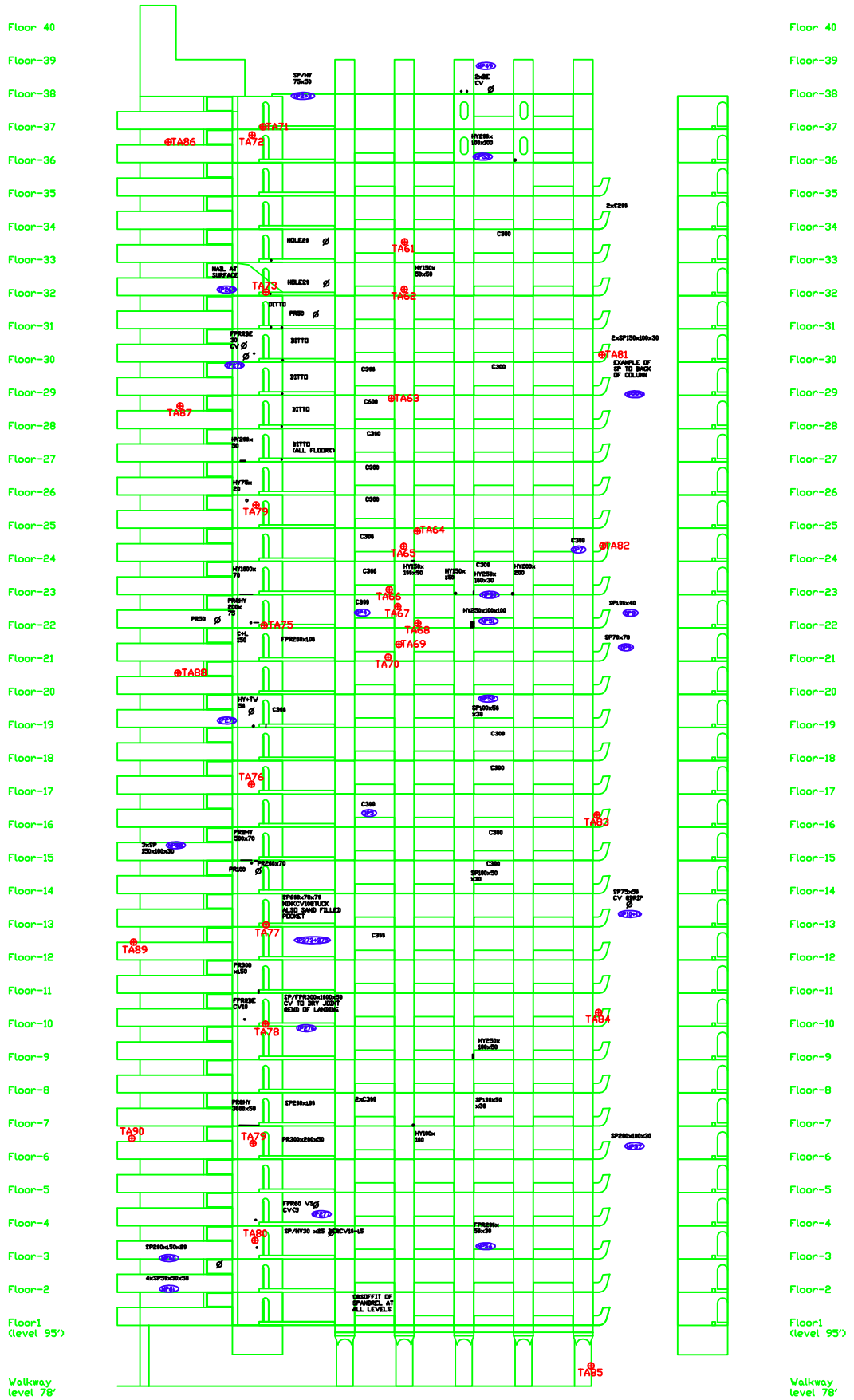
SHAKESPEARE ELEVATION A - SOUTH



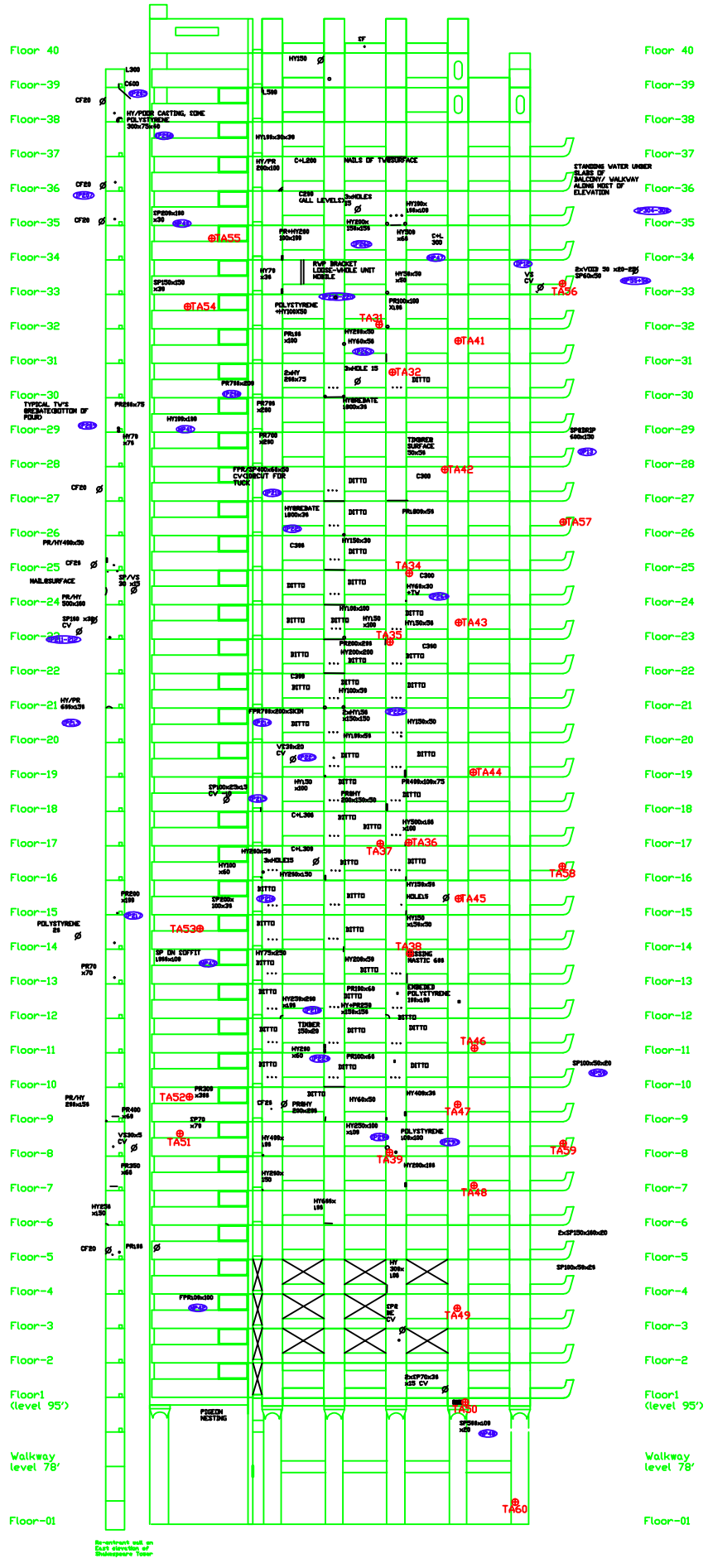
SHAKESPEARE ELEVATION B - EAST



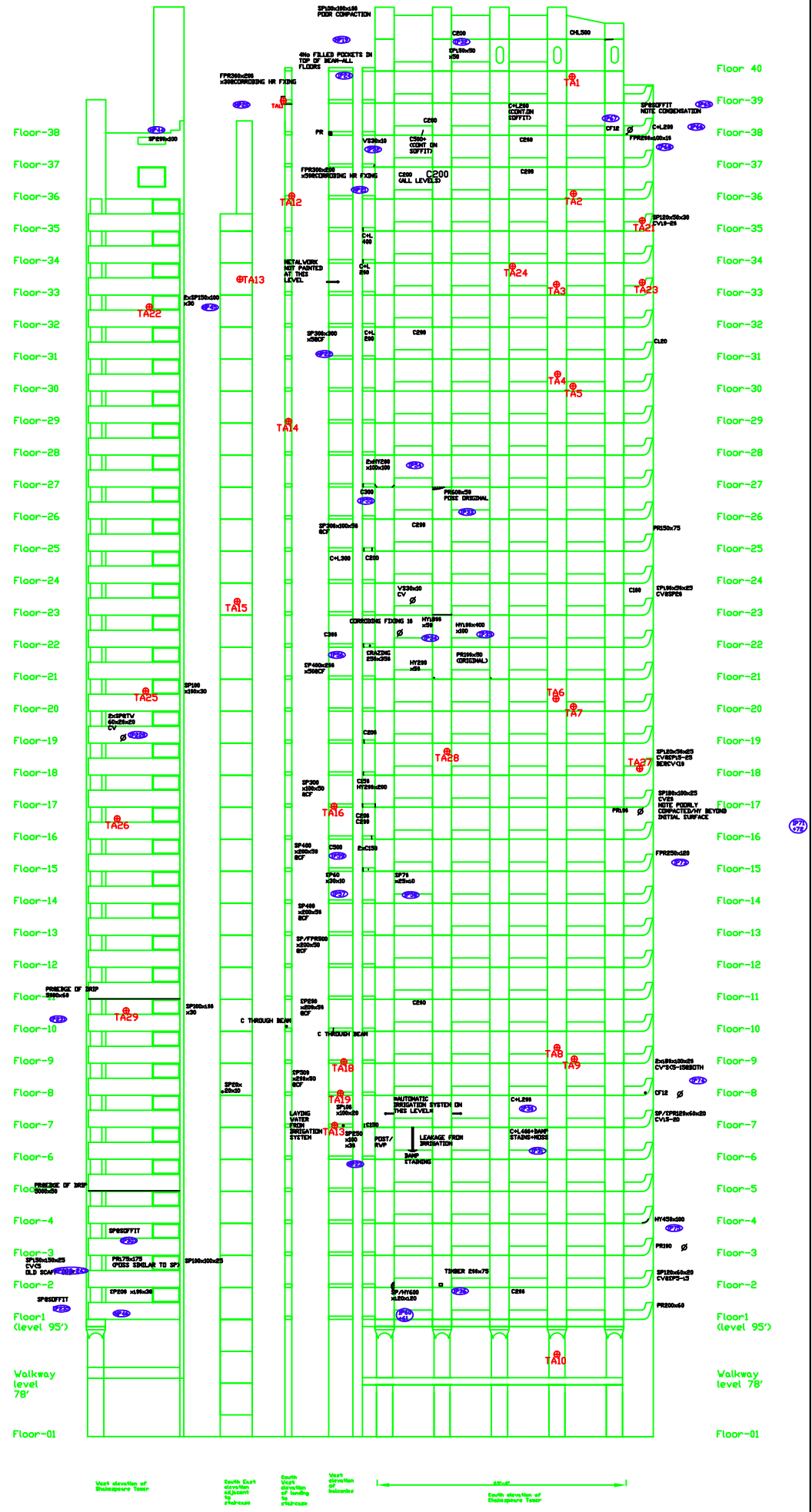
SHAKESPEARE ELEVATION C - NORTHWEST



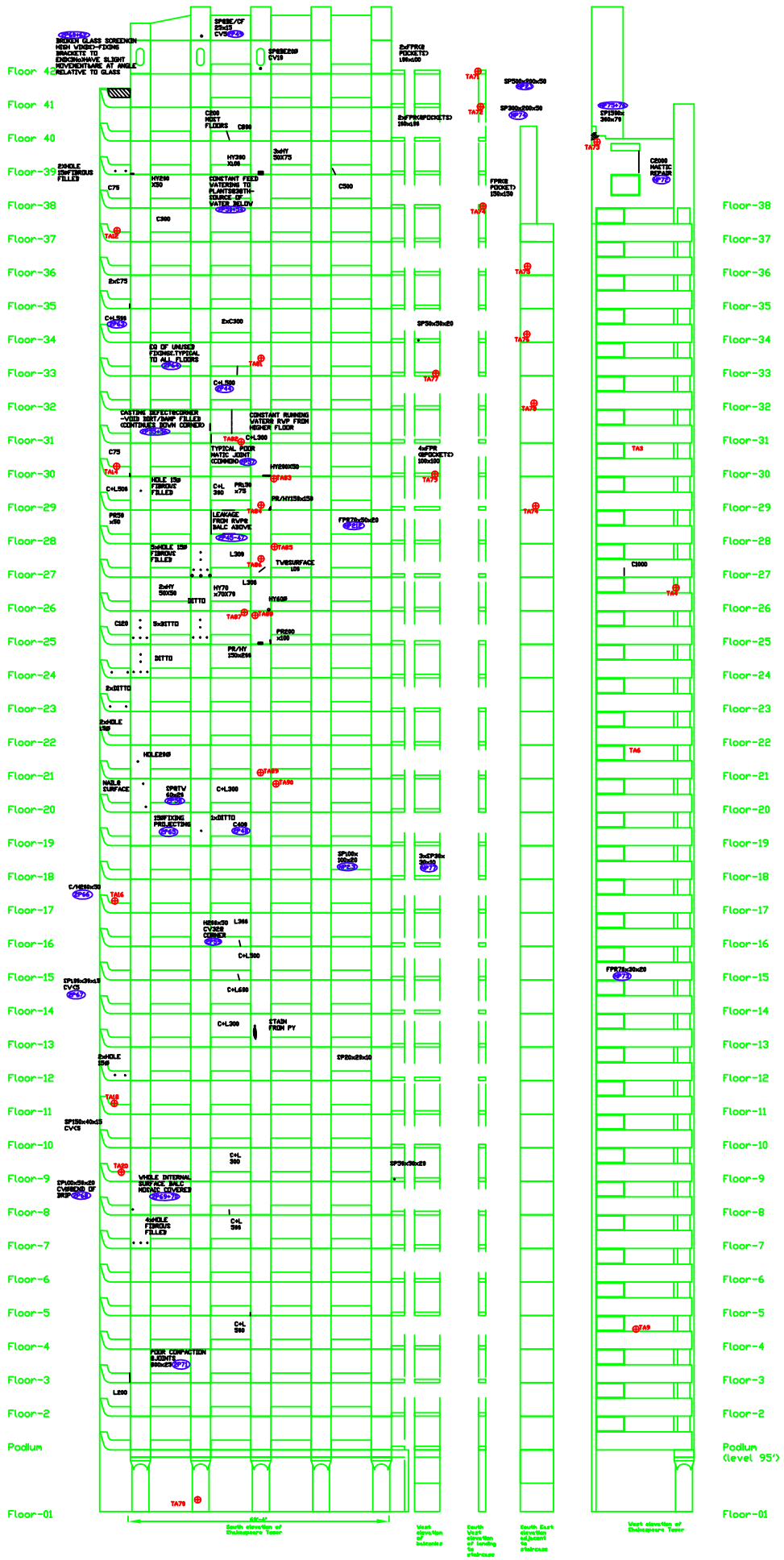
CROMWELL ELEVATION A - EAST



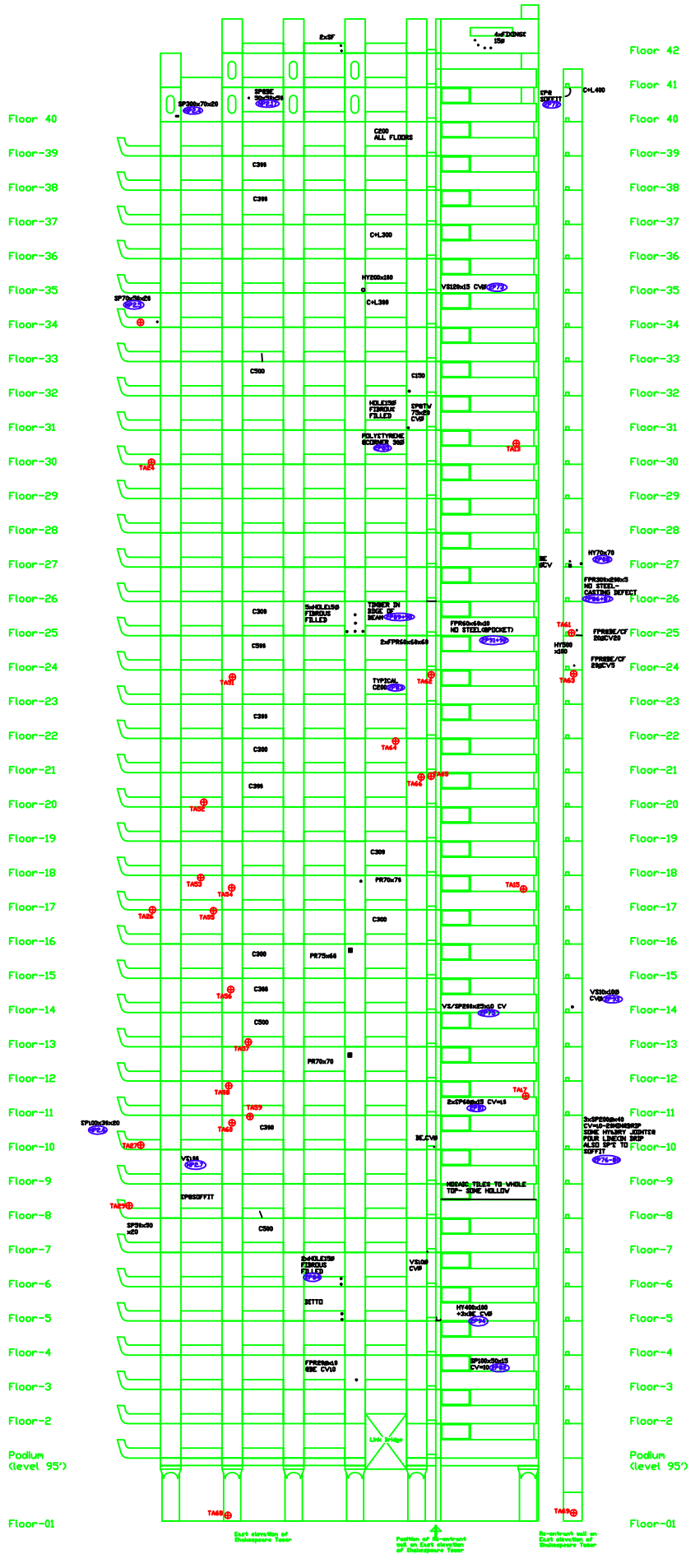
CROMWELL ELEVATION B - NORTH



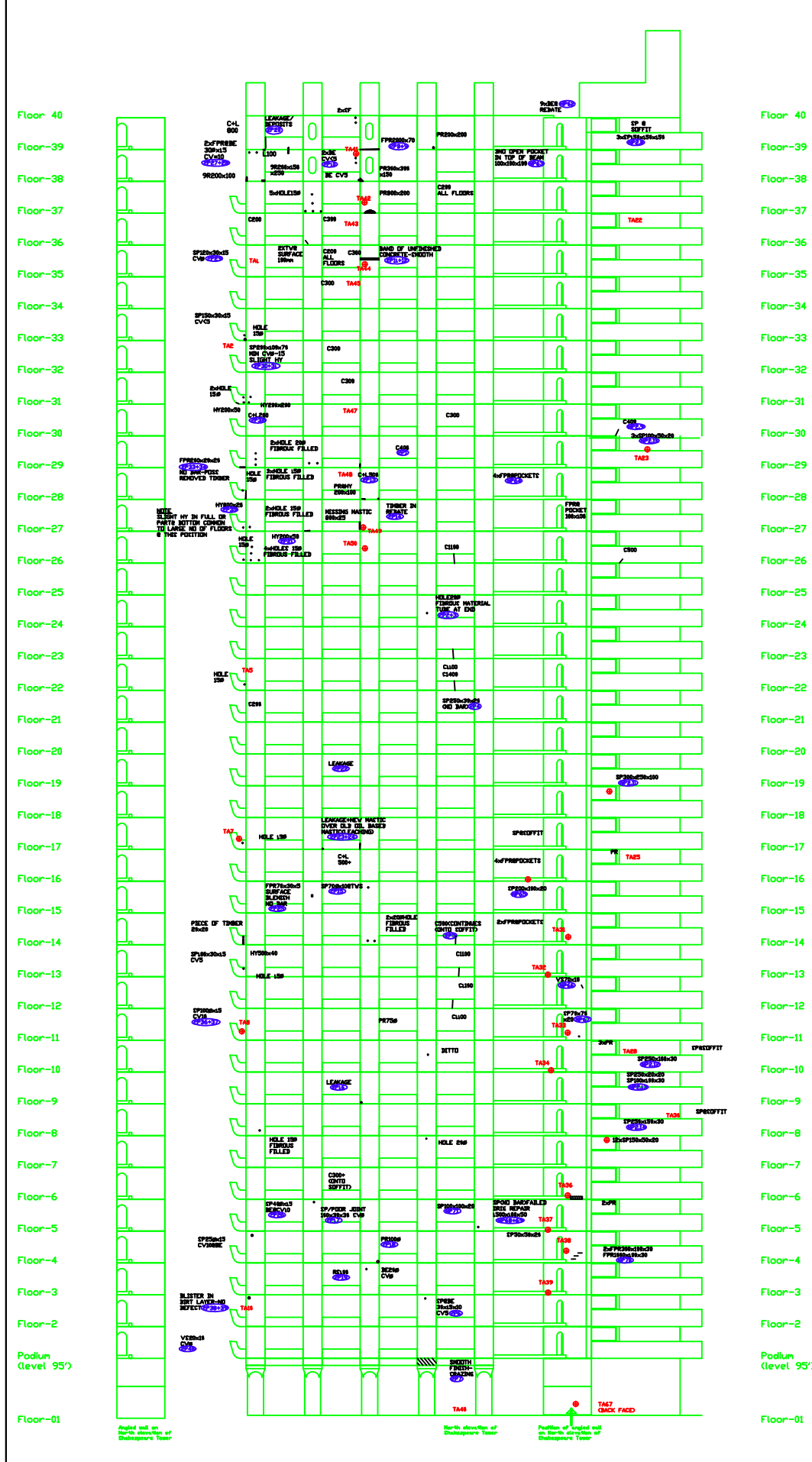
CROMWELL ELEVATION C - SOUTHWEST



LAUDERDALE ELEVATION - WEST



LAUDERDALE ELEVATION - NORTH



LAUDERDALE ELEVATION - SOUTH-EAST