Proposed Method Statement for Reinstatement of Cantilever Stone Stair

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For MAP Projects
2 Elizabeth Street
London
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1.0 Introduction

Packman Lucas were appointed by MAP Projects to provide a method statement for the reinstatement of a cantilever stone stair within the residential property at 2 Walton Street. The existing building is a 4 storey plus basement mid terrace Georgian townhouse which is wider at the front than the rear due to it being at the point where terrace cranks slightly. This can be seen from the approximate plan shown below in figure 1.

![Figure 1 – Key Plan](image)

The original stair was partly removed during previous renovation works when the building was converted into a number of individual flats. The proposal is now to return the ground to third floors back to a single townhouse with the original stair reinstated as closely as possible.

2.0 Existing Staircase

The existing staircase between ground and third floors is a mixture of two styles of construction. Between second and third floors the original stone staircase remains which is being used as a guide for the reconstruction of the lower flights. Between ground to first and first to second floors the top half of each flight remains as the original stone stair with the bottom half of each flight having been replaced with timber during the previous renovation works. This can be seen in the adjacent image where the original stone treads are shown in green and the proposed treads in red.

As cantilever stone stairs are not true cantilevers and rely upon support from each of the treads below, it is
currently assumed that the later timber infill portion of the staircase is currently providing support to the final tread in both the first and second stair flights. More details with regard to the construction and structural form of cantilever stone stairs can be found in appendix A.

3.0 Proposed Method Statement

The majority of the stone stair to be reinstated will be located within the existing party wall to the south elevation which is currently providing support to the remaining flights and is assumed to have supported the original sections that were removed. As we have not carried out any opening up works on site, this assumption will need to be confirmed at the outset of the project when the timber portion of the stair and the finishes can be removed. At this stage it is likely that evidence of the original stair will be seen behind the finishes with the ends of the original stone treads likely to still be present within the masonry. Based on this assumption, the proposed sequence for reinstating the stone treads to the lower halves is as follows:

- Leading edge of stone stairs between ground and second floors are to be fully propped and the timber section of the staircase and partition walls removed in accordance with the architect’s demolition plans.
- The finishes to the party wall are to be removed and the existing masonry exposed along with any remains of the original stair ends which may still be within the wall.
- Temporary props with strongboys are to be installed above the proposed stair flight to prop the masonry above approximately 600mm (8 courses) above the treads – refer to figure 2 below.

![Figure 2](image)

- Masonry removed to a depth of 115mm as shown.
- The tread bearings are to be made good ensure that they are level to receive the new treads.
• Reinforcement to be installed and concrete shutters placed to profile of proposed stair with a 40mm gap to required level of treads – refer to figure 3 below.

![Figure 3](image)

• Stair treads are to be installed sequentially from top to bottom with each tread being installed fully and grouted prior to proceeding to the next tread in order to ensure full load transfer between the treads.

• Each tread is to be installed and levelled with the tip propped. A flat jack is to be installed between the top of the tread and the new RC spreader beam and then inflated to the required pressure to ensure the tread is securely fitted within the existing wall – refer to figure 4.

![Figure 4](image)

• Jack is to be grouted and allowed to cure before proceeding to the next tread down.
The above method relies on the final tread of the flight also having a suitable bearing that is sufficient to resist the vertical loads that are to be transferred down through the new stair flight onto the landings at ground and first floors.

Where the stair flight returns at the bottom of each flight it is to be constructed within a new loadbearing masonry wall which will be constructed at the same time of the stairs and fully dry packed at each floor level to ensure the load from the walls above is adequately transferred to resist the forces applied from the stairs.
Appendix A
Stone cantilevered staircases

Synopsis
Cantilevered stone staircases have been in use in England for over 350 years. For at least 200 of these years they were the standard answer for the principal flights in almost all decent town houses. Many thousands must have been built in this country and across Europe. Practically all of them are still in use today, so one can say with confidence that they have stood the test of time and are structurally sound. And yet there are still concerns about their real strength, as shown by recent correspondence in New Civil Engineer and on the ICE website. Problems like the dislodging of a tread at the bottom of a flight in Bedford Square raise worries, and engineers asked to check and approve existing stairs for crowd loading are uncertain how to proceed. The purpose of this paper is to throw some light on the structural mechanics of these stairs, and to propose a method for calculating the stresses. The paper concludes with some examples of new staircases designed by the authors, made of stone, of precast concrete and of wood.

History
Cantilevered stone staircases were introduced into England as a result of Inigo Jones’s visit to Italy in 1613. He saw Palladio’s staircase in La Carità (now the Academia) in Venice, which was built about 1560. It is elliptical in plan and has 96 steps and eight landings. Palladio describes it in the Quattro Libri dell’Architecture in the chapter ‘Of stairs and various kinds of them’. He writes, ‘they succeed very well that are void in the middle, because they can have the light from above, and those that are at the top of the stairs, see all those that come up, or begin to ascend, and are likewise seen by them.’ This description perfectly captures the feeling of the quality of space in these staircases. He goes on to write, ‘I have made a staircase which is void in the middle, in the monastery de la Carità in Venice, which succeeds admirably.’ (Fig 1). This little boast inspired many architectural scholars to visit the staircase. Goethe wrote in his diary after visiting, ‘About a small stairway (a spiral without a column in the centre) which he himself praised in his work – which succeeds marvellously – I believe I have said nothing. Indeed, it is nothing except a spiral stair, but one which a person never grows weary of going up and down.’ Palladio definitely considered using these staircases in other projects. A series of 20 sketches of alternative plans for the rebuilding of the house of Camillo Volpe in Vicenza c.1569 all show them. This drawing went on to be owned by Inigo Jones, then John Webb, then William Talman, and then Lord Burlington – all of whom went on to design cantilevered stone staircases in their buildings.

Inigo Jones took the trouble to sketch Palladio’s staircase in his copy of Quattro Libri when he visited Venice. It must have inspired him to design the Tulip Stair in the Queen’s House in Greenwich in about 1630 (Fig 2). This again is built in an open well, but is much more refined than Palladio’s staircase. The soffit of each tread is scalloped and each tread is rebated onto the tread below. Nicholas Stone, who was the mason for the project, may have collaborated with Jones on these details. (He was the King’s Master Mason at the time.) It must have been easier to position the treads correctly with the addition of the rebates.

Wren and Hooke designed the next cantilevered stone staircase in England, in the Monument to the Great Fire of London, built in 1671. The staircase is a tight circular spiral of rectangular section treads, made from Belgium Limestone and rebated together except for the first few treads, which are supported by walls at both ends (Fig 3). The change from plain to rebated treads is structurally significant and will be
A major step in the development of these stairs was the realisation that it was possible to make the treads triangular in cross section, giving the flight a swept soffit. The first of this kind may have been built by Christopher Kempster, on a small pavilion in his hometown of Burford in about 1690 (Fig 4). Kempster worked closely with Wren on a number of the city churches and his son was the mason for the spectacular Geometric Stair in the southwest tower of St Paul’s Cathedral. Triangular shaped treads have the advantage of being only a little over half the weight of the equivalent rectangular tread and use less stone. They are always rebated. In the late 18th century the triangular section tread was universally adopted and huge numbers of town houses have them in their principal staircase.

In the 18th century designers of grand country houses put the main staircase in the central hall as the showpiece of the interior. The first to do this was Talman with the Great Stair at Chatsworth, built about 1690. This staircase stands in a wide rectangular hall. The first two flights are enormous at 2.1m wide. The treads are rectangular, made from Millstone Grit, (which is a particularly strong stone) and have small rebates. Staircases continued to be refined, and a particularly fine example is the staircase at Townley Hall near Dublin, designed by Francis Johnston in the 1790s. This is in a circular drum, has a swept soffit, and a very slender landing, and is made from Portland stone.

We have not been able to discover how far the treads of the earliest stairs were built into the supporting walls. The treads of the stairs at Hampton Court (1700) are generally built 9in into the brickwork, and those of the Geometrical Staircase at St. Paul’s Cathedral (1705) are built 6in into the stonework. The treads of 19th-century staircases were invariably built 4\(\frac{1}{2}\)in into supporting walls made of brickwork. In Victorian houses one occasionally finds the staircase supported on a wall that is only 4\(\frac{1}{2}\)in thick; in some cases we have even seen supporting walls made of timber stud with brick nogging. This makes it very clear that the treads are not cantilevering!

**The true cantilever**

A common example of a true ‘cantilever staircase’ is the set of stone steps that allows the Lakeland farmer and his dog to get over a dry stone wall (Fig 5). The weight of the stone above tails down the step. A simple sum will show that this works so long as the wall is at least 300mm thick and the slab projects not much more than about 300mm from the face of the wall. Even so the top step is only just stable, as anyone who has climbed over these walls will know.

The stability of a stone staircase, and particularly the top landing, can be provided in the same way as the step in a Lakeland wall if the wall supporting it is thick enough and there is enough weight from the wall above. Again a simple sum will show that the weight of a stone slab carrying some live load and projecting about 1m from a 340mm thick wall will not develop tension in the wall if there is about 8m of brickwork above. The same sum for a 225mm thick wall gives a necessary minimum height of about 16m! These heights assume that there are no other loads on the wall, which in practice there usually are. They also assume that the plan length of wall tailing down the cantilevering slab is the same as the length of the slab. In practice there is often a greater length of wall than of slab, although the assumed condition might apply to the long top landing of a large staircase. The sum also shows that the bending stress in the stone will be less than 1.0N/mm\(^2\), which is well within the safe stress for most building stones.

These heights of wall needed to support a true cantilever are so great that they are only likely to be achieved in exceptional circumstances. In the fairly typical case of the Victorian terrace house the stone staircase only goes up to the first floor. At this point the staircase changes to timber, and the wall beside the staircase changes to stud with lath and plaster. There is therefore very little load from the wall on the top few treads of the stone staircase. So it is quite clear that in the general case of the Victorian staircase the treads and landings do not cantilever.
The mechanics of the ‘cantilevered’ staircase

So, the first thing to be said about ‘cantilevered’ stairs is that they do not cantilever. We have used ‘cantilevered’ because this is the name by which they are generally known. They are also sometimes called ‘hanging’ or ‘geometrical’, and in Scotland ‘Pencheck’, but none of these adjectives is accurate. They do not hang, the significance of geometry is not obvious, and they do not cantilever. An accurate but long-winded description would be ‘stairs that are supported on only one side of the flight’. This conveys the dry structural message, but is inadequate as a description of a piece of architecture, and quite fails to convey the feelings that Palladio described in the *Quattro Libri dell’Architettura*.

It was no doubt the masons who discovered and understood the principles of the ‘cantilevered’ staircase. (Palladio was apprenticed to a stone mason.) In the seventeenth and eighteenth centuries the principles must have been passed on from mason to mason, and in the nineteenth and twentieth centuries they were explained in several books, e.g. in C. W. Pasley’s *Observations on Limes, Calcareous Cements etc* (Pasley, 1838) and in Joseph Guilt’s *Encyclopaedia of Architecture* (Guilt, 1844). *Mitchell’s Building Construction* (Mitchell, 1936) contains a drawing of a stone staircase, fully dimensioned but without any explanation of the principles. However, more recently, possibly only since the Second World War, the understanding of this form of construction seems to have been lost. Any engineer trying to build one of these stairs today is likely to have his/her work cut out to persuade the building inspector that it will be safe.

An incident in 1985 during the building of a new staircase in a shop in Covent Garden revealed with complete clarity the structural principles of ‘cantilevered’ stairs. The staircase (Fig 6) was for a shop in Neal Street. It was to be built of second-hand railway sleepers cantilevering out of a reinforced concrete wall. The sleepers were to be set about one inch apart in order to give the required rise, and so would be completely independent of each other, acting truly as cantilevers. To construct the stair the builder first put up the front shutter for the concrete wall, made out of 19mm plywood with ‘letterboxes’ cut into it, and then ‘posted’ the treads into the letterboxes. They were a good fit, so that the joint would be reasonably grout-tight. Small packs were placed between the treads at the outer corners in order to hold them the right distance apart and the bottom tread was supported off the floor (Fig 7).

At this point the builder found, to his great surprise, that the staircase was quite rigid in this condition, and could easily support a man. It was obvious that the treads could not possibly cantilever out of an 8ft high sheet of unsupported plywood; it took a moment to see that the weight was being transferred from tread to tread through the small timber packs, with the plywood providing torsional restraint, as well as vertical support, to the end of each tread. This is in principle how ‘cantilevered’ staircases work.

Plain treads without rebates

We have emphasised the structural significance of the joint between the treads, and whether it is plain or rebated. The simplest form structurally has plain unrebated treads, as shown in Fig 8. This sort of staircase is commonly found in the basement flight of Georgian terrace houses. Each tread carries the weight from the stairs above on its back edge and is supported under its front edge by the tread below (Fig 11). The wall carries the torsion resulting from these two forces. As the load increases down the flight, so the torsion increases, with the penultimate tread carrying the greatest torsion and the last tread being supported on the floor. In a straight flight of 15 treads, the torsion in the penultimate tread should be well within the strength of the stone, but the stresses in the wall will be quite high, particularly for soft bricks in lime mortar (see analysis below). This may be why unrebated treads are normally only used where the staircase wall is at...
least 9in thick and there is sufficient load from above to provide the necessary precompression. The very small twist in each tread resulting from the torsion allows the tread above to drop slightly. This twist can be calculated if one makes a number of assumptions about the properties of stone; in a long flight of 10 treads the calculated cumulative deflection could possibly come to anything from 3mm to 5mm at the top of the flight (Fig 9). Note that the deflection is normal to the slope of the staircase, so there is a horizontal component of the deflection as well as a vertical one.

Calculations for the stresses in a staircase

In proposing the following methods for calculating the forces in existing stairs we are well aware that there are a number of unknowns. For the design of a new staircase some of these may be eliminated by material testing and specification. In assessing the strength of an existing staircase the unknowns may include:

• the strength of the stone in the staircase
• the quality of the material in the supporting wall
• the quality of the mortar between the treads
• the way the staircase was built, i.e. tread on tread, or the whole flight on centring
• the vertical and horizontal support provided at the top and bottom of the flights
• the way the landing slabs have been jointed
• the strength and stiffness of the handrail.

There are of course unknowns in everything that an engineer does; material properties are not exactly known; and we make many simplifications in every analysis of a structure. We should not pretend to ourselves that we are dealing with pure scientific truth. Prof. Jacques Heyman has famously written, ‘If the designer can find a way in which the structure behaves satisfactorily, then the structure itself certainly can’. So, armed with the knowledge that we are not necessarily seeking the truth, we have developed the following methods of calculating the stresses in these stairs. By comparing our calculated deflections with observations of real stairs, sometimes under controlled load testing, we know that these calculations are conservative. They are nevertheless adequate to justify the loadbearing capacity of an existing staircase.

Analysis of the forces in the flight

It is assumed that:

• The supporting wall can resist forces in the plane of the wall in both vertical and horizontal directions, but not forces perpendicular to the plane of the wall.
• The supporting wall can resist moments in the plane of the wall, i.e. torsion from the treads, but not bending in the wall about either axis.
• The bottom tread is supported vertically on a rigid foundation.

Fig 10 shows the top tread of a flight, with no applied load except the self-weight of the tread, W, in the middle. The tread below will provide support in some way along the line AB, with the centre of the support, R1, at a distance of k1L from corner A. The wall supports the tread on its centreline with a vertical reaction R2 and a moment T1.

Taking moments about AD gives:

\[ R_1 \times k_1 \times L = \frac{W \times L}{2} \]

so, \( R_1 = \frac{W}{2k_1} \)

Resolving vertically gives:

\[ R_{w1} = W \left( 1 - \frac{1}{2k_1} \right) \]

Taking moments about the centreline gives:

\[ T_1 = \frac{R_1 \times b}{2} \]

\[ : T_1 = \frac{Wb}{4k_1} \]

The minimum torsion in the tread occurs when \( k_1 = 1 \) i.e. the tread is supported at the point B (an unlikely, or even impossible, situation), and \( R_1 = R_{w1} = \frac{W}{2} \) and the torsion is \( \frac{Wb}{4} \).

Now consider the next tread down, (Fig 11) and assume that this tread is supported similarly by the tread below, at a distance \( k_2L \) from the wall.

Moments about AD gives:

\[ R_2 \times k_2 \times L = \frac{W \times L}{2} + W \times k_2 \times k_1 \times L \]

so, \( R_2 = \frac{W}{k_2} \) \hspace{1cm} (1)

Resolving vertically gives:

\[ R_{w2} = W + \frac{W}{2k_2} - R_2 \]

so, \( R_{w2} = W \left( 1 + \frac{1}{2k_1} - \frac{1}{k_2} \right) \) \hspace{1cm} (2)

Moments about the centreline gives:

\[ T_2 = \frac{W}{2k_2} \times \frac{b}{2} + \frac{R_2 \times b}{2} \]

so, \( T_2 = \frac{Wb}{4k_2} + \frac{Wb}{4k_1} \) \hspace{1cm} (3)

It can be seen that the reaction under the nth tread is:

\[ R_n = \frac{2W}{2k_n} \]

So the reaction between two treads depends only on the number of treads above and the position of the centre of the area of contact between the two treads. It is not affected by the positions of the areas of contact between treads higher up the staircase.

The general equation for the torsion in the nth tread is:

\[ T_n = \left( \frac{n-1}{2k_n} \right) \times \frac{b}{2} + \frac{W}{2} \times \frac{b}{2} \]

\[ \text{i.e. } T_n = \frac{Wb}{4} \left( \frac{n-1}{k_n} \right) + \frac{Wb}{4} \]

The torsion in a tread is therefore affected almost equally by the position of the points of contact with the treads above and below.

Fig 10. (Left) Diagram showing the forces on the top tread in a flight of unbored treads (courtesy Ian Fussell)

Fig 11. (Left) Diagram showing the forces on the next tread in a flight of unbored treads (courtesy Ian Fussell)
If the $k$s are equal then
\[ T_n = \frac{Wb (2n-1)}{4k} \]

The minimum torsion occurs when both points of contact are (theoretically) at the extreme ends of the treads,
\[ i.e. k = k = 1 \text{ then } T_n = \frac{(2n-1)Wb}{4} \]

In the more likely case where $k_{mn} = \frac{3}{4}$, say
\[ T_n = \frac{(2n-1)Wb}{3} \]

It is interesting to see what sort of forces and stresses are involved. The weight of a stone tread 0.9m long $\times$ 0.25m wide $\times$ 0.175m high is about 1.0kN (a little less than the BS 6399 point load, and considerably more than the equivalent UDL for a domestic staircase). In a straight flight of 15 treads the torsion (with $k_{mn} = \frac{3}{4}$) in the first suspended one, i.e. no.14, under dead load alone, will be
\[ T = (2 \times 14 - 1) \times 1.0 \times 0.225 = 2kNm \]

The torsional shear stress $\tau$ is
\[ \tau = \frac{2.0 \times 10^6}{0.23 \times 250 \times 175^2} = 1.14N/mm^2 \]

Which is a reasonable shear stress for stone. If the staircase was loaded with one British Standard Man per tread (a considerably higher load than the British Standard uniformly distributed live load) this would about double the above figures, which would still be an acceptable stress for the stone.

The total angular twist due to this torsion, assuming that the stone is an elastic homogeneous material with a Young’s Modulus of $20 \times 10^6$N/mm$^2$ and a Poisson’s Ratio of 0.2 (!) is
\[ \frac{TL}{GJ} = \frac{2.0 \times 10^6 \times 900}{0.2 \times 20 \times 10^3 \times 0.19 \times 250 \times 175^2} = 1.8 \times 10^{-3} \text{ rad} \]

The back of the tread would drop 0.44mm.

If the effect of this rotation in all the treads is cumulative the total deflection of the top tread of the 15 tread flight will be about 3.5mm.

Movement of this order can sometimes be found at the top of a flight.

Stresses in the supporting wall
If there is a reasonable amount of vertical load on the wall then the torsion will be taken mainly by stresses across the bed joints. If the treads are built in 115mm the maximum stress in the masonry due to the torsion at the bottom of the 15 tread flight will be
\[ 2.0 \times 10^6 \times \frac{6}{115 \times 250^2} = 1.67N/mm^2 \]

This is quite a high stress for soft bricks laid in lime mortar, but probably acceptable for an isolated point.

Effect of a cracked tread
If the $(n+1)\text{th}$ tread is cracked right through at say a quarter of the tread length from the wall, i.e. $k_n = \frac{1}{4}$, and if $k_{mn} = \frac{3}{4}$, then the torsion in the $n\text{th}$ tread is
\[ T = (a - 1) \frac{Wb}{3} + \frac{Wb}{4} = (4n - 1) \frac{Wb}{3} \]

i.e. approaching twice the torsion on the tread if the one below was uncracked and providing support at the same distance from the wall. There will also in this case be bending in the $n\text{th}$ tread of
\[ \left(\frac{n-1}{2k} - k\right) \times \frac{W}{L} + W \left(\frac{L - k}{2} - L\right) \]

which for $k_{mn} = \frac{3}{4}$, and $k = \frac{1}{4}$ is
\[ \frac{WZ}{3} + \frac{WZ}{4} \]

For example if the 14th tread of the 15 tread flight is cracked in this way then the moment in the 13th tread will be
\[ 12 \times 0.9 \times \frac{1}{3} + 0.9 \times \frac{1}{4} = 3.83kNm \]

and the maximum bending stress in the tread would be
\[ 3.83 \times 10^6 \times \frac{6}{250 \times 175^2} = 3.0N/mm^2 \]

This is about half the flexural strength of Portland Stone.

Rebated treads
Figs 12 and 13 show two types of rebated tread. Here again, the load from above coming down on to the back of a tread is carried by torsion in the tread onto the tread below. However the rebates key the treads together, so that any rotation in a tread will tend to push its neighbours apart. In other words the rebates allow horizontal forces to be transmitted between the treads (Fig 14). These forces, acting in opposite directions at the top and bottom of the tread, can produce a couple which opposes the couple of the applied loads. This reduces

![Diagram of forces on a rebated tread](courtesy Ian Fussell)
very considerably the stresses in the treads. A flight with rebated treads has even more unknowns than a flight with plain treads. To simplify the analysis the conservative assumption can be made that the horizontal restraint is only applied at the landings and that the horizontal force is therefore constant throughout the flight, producing a constant couple in all the treads (Fig 15a). In the case of a straight flight with stone landings at the top and bottom, the landings can restrain the flight, and so develop the horizontal force that reduces the torsion in the treads. The couple due to the vertical loads still increases down the flight, as for the plain tread (Fig 15b). The resultant net torsions in the treads are shown in Fig 15c. So, for the flight shown schematically in Fig 16 there is a net clockwise torsion on the lower treads, where the moment from the vertical loads is greater than the moment from the horizontal force, and there is a net anticlockwise torsion in the upper treads, where the moment from the horizontal force is greater than the moment from the vertical loads. The middle tread is in balance. The rotations are symmetrical, giving the deflected shape shown in Fig 16. The mid-flight deflection will be a quarter of the deflection at the top of a similar flight of unrebated treads. Fig 15c shows the effect of the rebates. The maximum torsion on a tread is halved. The stresses in the supporting wall are reduced even more significantly, because the torsion at the wall will be largely provided by the stone-to-stone connection. The wall only has to supply the additional torsion to carry the load from that tread, rather than the whole torsion that would be required by unrebated treads.

It is acknowledged that there are a lot of unknowns in this simplified analysis of a flight made with rebated treads. The value of the horizontal force between the treads is difficult to assess, as it depends not only on the stiffness of the stone and of the supporting wall but also on the end restraints to the flight i.e. how the flight is supported, both vertically and horizontally, at the landings. The detailing of the stones in the flights and landings could affect the way the staircase works, as could the way in which it was built.

One way of testing the accuracy of this analysis is by measuring the deflection in a real flight under a load test. We have had the opportunity to do this on a few occasions, and the actual deflections have always been less than predicted, and usually so small as to be difficult to measure. This indicates that the assumptions made in this simple analysis are conservative.

Modern scientific analysis may not be able to predict accurately the stresses in the treads, but the builders of the late 18th century knew what was going on. They put their faith in the rebates and cut the treads down to the elegant triangular section that became the standard for the 19th century. This reduced the torsional strength of the tread to about a third of its rectangular counterpart and reduced the stiffness to about a sixth. Such dramatic reductions could only be possible with rebated treads.

**Landings within the flights and at the top of the flight**

The Fountain Court at Hampton Court contains a wonderful collection of stone staircases designed by Wren, or more probably Talman. The ‘Beauty Staircase’ has a landing within the flight (Fig 17). Here the landing slabs are rebated onto each other, and the load is transmitted in the same way as it is between the treads in the flight. Similar detailing is normally used at landings at the top of staircases, which can be made up of many separate pieces rebated to each other. An alternative to the rebated joint is the joggled joint, normally lead-filled.

**Landings at changes of direction**

Again, at Hampton Court, it is possible to see how the flights and landings are interacting by looking at the detailing of the rebates. The general arrangement, for quarter or half landings, is to build the corner pieces of the landings into the two walls of the stairwell. As these pieces of stone are supported...
on two walls at right angles they can provide a rigid support for the flight or landing.

This means that in effect the whole staircase is made up of structurally independent flights, with pieces of the landing fitting between. In Fig 18 the stones making up the half landing are lettered A to E. The lower Flight 1 is propped horizontally by stones C, D and E, with stone E spanning between the top of the flight and stone D, which is built into both walls. The load of the upper Flight 2 is carried by landing slab A on to the corner slab B, which is built into both walls. In some of the stairs a crack has opened along the line of the rebate between the top tread and the landing, i.e. below stone E, which shows that the horizontal force from the landing has not held the top of the flight (probably due to the rebate being too shallow). It also shows that the lower flight 1 is not supporting the landing.

Spiral staircases

Spiral stairs with unrebated treads behave in principle in the same way as straight flights of unrebated treads. The torsional stresses in the treads are less than the stresses in a straight flight because the width of the tread at the outer edge is less than the width at the wall. The eccentricity of the vertical forces that cause the torsion is therefore less, while the section of the tread resisting the torsion is greater. In spirals with rebated treads the horizontal forces developed by the rebates can be restrained throughout the staircase by the enclosing wall, and it is likely that very little, if any, torsion is developed in the treads.

Failures and repairs

With such a large number of these stairs in use it is not surprising that there have been some failures. Like any piece of structure they can be overloaded, and unlike structures made out of...
materials that are elastic and ductile, they can crack suddenly. In our experience this is probably usually caused by overload of an individual tread. This does not necessarily lead to the failure of the flight (Fig 19). We have seen staircases that have stood quite safely for years with treads cracked right through. As long as part of the cracked tread remains intact and in place at the supporting wall the stability of the treads above can be maintained, as shown in the analysis above.

New stairs
Since we became interested in this subject we have designed over 30 new cantilevered staircases. Some have followed traditional patterns and some have been in a contemporary idiom. They all use the same structural principles. We often work directly with the stonemasons, and for complex geometrical staircases we produce complete three dimensional computer models of the entire staircase. The face moulds needed for carving the treads are produced directly from the model. Fig 20 shows an example of this work. This staircase is built in a stretched octagon shaped tower with an elliptical central well. Every tread in this staircase is unique. The staircase is made from Portland stone and has recently been completed. Fig 21 shows a tread being installed on a staircase that is currently under construction. The masons are using a vacuum pump lift to place each tread in position. The mason guiding the tread is kneeling on a tread that was installed only a few minutes earlier.

The staircase at da Costa House in Highgate (Fig 22) was designed with Russell Taylor in homage to Inigo Jones, and is based closely on the Tulip Stair in the Queen’s House. The treads are made of very high quality precast concrete, finished to resemble stone. They are supported on a 4½in thick brick wall, which is tied to the block wall that supports the concrete floors. The block wall was built first, in order to get the shell of the building up and watertight, and the staircase and its supporting wall were built later in order to avoid damage to the pre-finished treads. It is quite possible that this technique was used in earlier centuries for the same reason.

Fig 23 shows a staircase made from high quality precast concrete only 60mm thick. This stair works in principle just like a stone staircase with rebated treads. This has been designed and detailed in a way that expresses very clearly the structural form of the staircase. The bolted joints between stone and steel show that there is no cantilever action and that the stair stands by torsion in the treads, transferred into bending in the string.

The timber and steel staircase designed with Susan Walker Architects in Fig 24 is in a private Victorian house in South Kensington. A steel plate with dowels welded onto it is fixed to the wall. The oak treads are resined onto the dowels and a steel collar threaded on to the baluster transmits the load from tread to tread.

Conclusion
This paper is in effect a report on work in progress. Our understanding of how these stairs work continues to develop. We have recently been looking at two stairs where partial failure has occurred, and this has helped us to confirm our view of the factors of safety.

We have recently arranged for a programme of tests to be carried out at the Engineering Department at Cambridge University. This will establish the properties of various building stones, and specifically the relationship between the flexural and torsional strengths. We are also intending to carry out in the near future a load test to destruction of an existing stone staircase in a Georgian house. When these tests are complete we may be able to refine our analysis further and produce an addendum to this paper.