HOW DOES THE NEW BUILDING STAND UP?

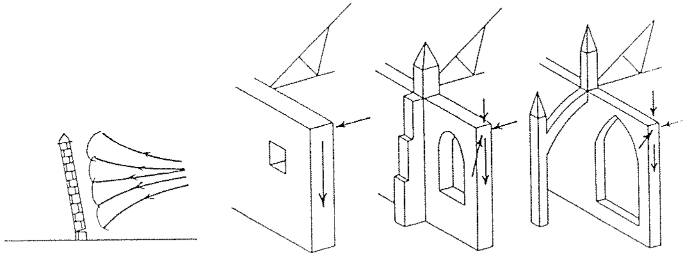
The new building nearing completion in the forecourt of the Master's Lodge will undoubtedly attract attention from architects, as do most of Michael Hopkins' buildings. But the building will also be visited by its fair share of structural engineers because of many innovations by the structural designers, Buro Happold.

Michael Hopkins takes pride in designing buildings in which the form of the building accurately reflects the way the building behaves. He wanted to build in Ketton stone, which was the material used for the Wren Chapel and the facing of the Westmoreland Building. But at the same time he wanted a modern building, with larger windows and smaller structural elements. In virtually every other modern structure, the visible surface is only a cladding, which hides the structural core which is, almost invariably, a reinforced concrete or steel frame. The result is an engineering challenge – how can you make such a structure, in stone, where the stone actually carries the load rather than being a facing on the surface?

The problem arises because stone is a material which is unable to carry tension – it simply cracks. If a stone wall has high lateral loads on one side, tension cracks will develop and it will collapse, as in Figure 1(a). This is the major cause of death in gales, when gable ends of buildings and boundary walls collapse under the action of wind pressure.

In a conventional building, horizontal loads come onto the wall at the roof level, partly due to the eccentric weight of the roof itself and partly due to wind loads. Over the centuries various ways have been found of resisting these loads. If the wall is thick, and therefore heavy, the weight of the stone counteracts the tension (as in Figure 1(b)). But this takes a lot of stone, so masons often build buttresses at intervals along the wall (Figure 1(c)). One of the original buttresses remains outside the Hall in New Court, and others can be seen all along the sides of King's College Chapel.

Figure 1



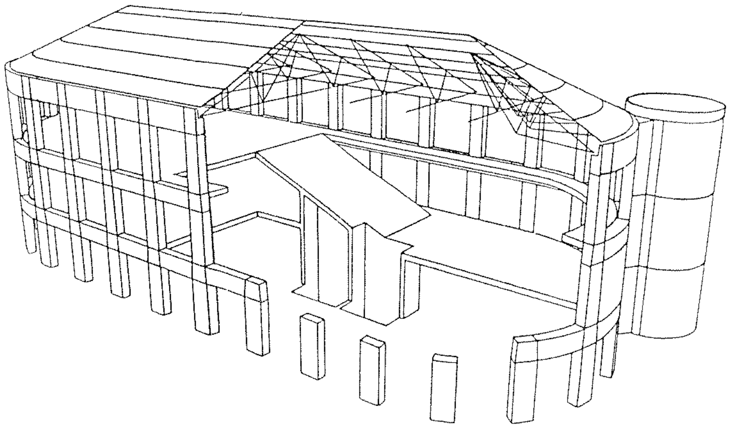
From left
(a) Collapse of wall due to wind loading and absence of tensile strength
(b) Solid wall, small windows
(c) Buttressed walls with pinnacles, bigger windows
(d) Flying buttress to walls with large windows

There were also often problems at the top of the wall, where there was insufficient weight to resist sliding. So masons sometimes added pinnacles – again seen to the best advantage in Cambridge by the examples along the walls of King's Chapel. The 'Dreaming Spires' at the other place near Cowley are mainly pinnacles of this sort.

The principle of the buttress is taken to its logical conclusion in the flying buttress, when the thrust of the roof is balanced by the inward thrust from the buttress (Figure 1(d)). The shape of these arches is critical, and in the absence of a proper understanding of structural mechanics, there must have been a lot of 'error' to go with the 'trial' before the light and graceful lines of the great cathedrals, such as Notre Dame in Paris, could be realised. Apart from a couple of decorative examples on top of New court in St John's, there are no examples of flying buttresses in Cambridge.

So how did Michael Hopkins and Buro Happold tackle the problem? Modern buildings don't have buttresses or pinnacles, and large windows cut out weight which helps to resist the load. The design of the auditorium called for an open roof space, with the roof itself, acting as a stiff cap, resting on top of 28 small stone columns around the perimeter. Although the building has a concrete core around the piano lift, and some small concrete walls around the lobby, there would be no connection between these elements and the outer structure at eaves level (see Figure 2). This meant that the columns would have to act as vertical cantilevers above the second floor level, where the columns would be tied to the core. To make matters worse, in the auditorium, which is two storeys high, there is only a narrow gallery slab at mid-height to restrain the columns, so in effect the columns tend to act as cantilevers over two storeys.

Figure 2



Cut-away view of New Building, showing structural elements only

The solution was to borrow an idea from concrete construction. In 1927, a French engineer, Eugene Freyssinet, discovered that he could apply a large compressive force to concrete, which eliminated tensile stresses completely. So the engineers chose to compress each of the columns; in effect, the column behaves as though it had a massive pinnacle on the top whose weight helps to resist the lateral loads. This is achieved by means of a stainless steel rod passing through each column which is preloaded by means of a hydraulic jack to a force of 25 tonnes. With this in place, any lateral load on the columns has first to overcome the compressive stresses caused by the preload before any tension cracks can develop. The rod also prevents any cracks that do form from opening to a serious extent.

The prestressing rod applies a concentrated load which could cause splitting if applied directly to the stone, so at each floor level there is a precast concrete kneeler block to spread the load. These have stainless steel fittings which allow access to the rods for inspection, and if it ever proves necessary, replacement, without having to disturb the rest of the structure.

As far as I am aware, this is the only occasion in recent times when a permanent stone structure has been prestressed, although church spires, which are thin stone shells, were often prestressed to a small degree to eliminate tension near the top. This was achieved by passing a rod vertically down from the top of the spire to a heavy timber beam which spanned the tower or crossing on which the spire was founded. This rod was often extended at the top to provide a weather vane, and at the bottom provided a convenient strong point from which to hang a chandelier.

The application of the prestress meant that the columns would be under permanent high stress, typically of the order of 2 N/mm2[1], rising to a peak stress of about 4 N/mm2 when lateral loads were applied. These seem small by comparison with stresses in concrete (about 10 N/mm^2), or the strength of an individual stone (typically about 20 N/mm^2). But they are more than twice as high as the stresses in a stone cathedral, so it was decided to test sample columns in the laboratories at the Cambridge University Engineering Department. These showed clearly that the strength of the column depends not just on the stone, but critically on the mortar. It is important to be able to transfer load from one stone to the next, without imposing uneven stresses. What is needed is not a modern high strength cement mortar, but a weak lime mortar (more like the traditional mason's putty) which gets squeezed out if a high load is applied at one point, leading to a more even load distribution. The tests resulted in the development of a carefully controlled mix design for the mortar and a method statement for the masons to follow to ensure an even load distribution. This method was applied to a full scale top storey column which was tested in a 500 tonne testing machine; the test column carried the full load the machine could apply without failure.

But the engineering innovation does not stop with the columns. The shallow arches over the windows are also new applications of old techniques. A conventional arch bridge works by developing a thrust that resists the applied vertical loads. This thrust follows the line of the arch, and has a horizontal component at the abutments which has to be resisted, either by the ground or by the thrust from an adjacent span. These thrusts can be quite large, and the shallower the arch, the greater the thrust. In many cases, the ground yields in response to the thrust, causing the arch to crack. Such effects can be seen in many bridges (for example, the sag in the Western span of Clare Bridge), and also in many churches. These cracks are not usually critical to the stability of the arch, which automatically adjusts its shape to carry the load, but they do look unsightly.

Before the invention of steel and reinforced concrete, the lintels that support the walls over windows were made in the form of shallow arches, with the joints between the stones or bricks inclined to the perpendicular to the thrust. Don't be deceived if the bottom of the lintel is horizontal – if the joints are inclined it is acting as an arch. A similar approach has been adopted in our building. Each lintel is formed from five shaped stones, known as voussoirs. The thrust passes through these voussoirs into the present concrete kneeler blocks, which are also shaped to match the thrust.

On the straight side of the building, the thrust from the lintels on either side of each column balance one another, so there is no tendency for the columns to bend. But on the curved ends of the building the thrusts from adjacent lintels do not line up, causing a net outward force to be applied to the column. This has to be balanced to counteract any tendency of the column to bend outwards. To achieve this, the engineers have made use of a property of the concrete floors which is, in most cases, a nuisance. Concrete shrinks after it has hardened, due to the evaporation of surplus water left over when the chemical reaction is complete. The shrinkage is small – typically 1/30th of a percent, but it is the reason why concrete roads are built in sections, with joints every few metres where movement can take place without causing problems. In our building, the floor slabs have been tied to the columns via the kneeler blocks, so that as the concrete shrinks the inward movement of the slab will apply a force to the column to counteract the outward thrust from the lintels. Very ingenious.

A similar problem occurs with the roof, which is lead covered and has substantial self weight to provide the required acoustic isolation to the auditorium. This has some benefits in that it increases the vertical load on the columns below but it has a penalty in that the stainless steel and timber roof trusses must spread to take up the strain as the load is applied. It also applies its load eccentrically to the stone column which is itself counteracted by a slight offset in the position of the prestressing rod. As with the lintels on the lower floors, this is not a problem on the straight sides, since the trusses have a bottom tie rod which is drawn in to counteract the spreading of the truss under load. But at the curved ends the force must be transmitted straight to the columns. The original design had a series of rods running inside at eaves level to transmit this force from one end of the building to the other, but these forces have now been incorporated within the precast gutter units which sit on top of the lintels.

So the College, and Cambridge, will soon be blessed with a modern stone building that blends in with the other college buildings and will give us a number of public rooms that will be useful for many purposes. It will be simple to look at, and will be hailed as a good piece of architecture. But it won't be a bad piece of engineering either.

I am grateful for the assistance of Michael Dickson and Geoff Werran, structural engineers with Buro Happold, for information about the thoughts that lay behind the structural design of the building.

C J Burgoyne

1 The units may not be familiar to many people. The standard unit of measure for pressure or stress is the N/m^2. 1 Newton is about the weight of one apple (very appropriately), and the area of a domestic table top is about 1 m^2. So a pressure of 1 N/m^2 is equivalent to the load induced by smearing an apple out over a table top. This is much too low to be useful, so engineers use N/mm^2 (Newton per square millimetre) as the standard unit of stess. This is equivalent to putting a million apples on your table top.