

# The Structural Engineer

The flagship publication of the Institution of Structural Engineers



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IN COLUMNS**

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OF REAL SLABS**

**YORKSHIRE  
REGIONAL GROUP  
PROFILE**

**ADMIXTURES**



## SANDS OF TIME

What happened to the cladding  
of Egypt's ancient pyramids?

# Viewpoint



Cintec's Managing Director Peter James has been involved in the restoration of some of Egypt's oldest structures for the past 14 years. He explains why the missing cladding from Cairo's ancient pyramids may not be down to opportunist thieves after all...

## Missing cladding of Cairo's pyramids

### From mosques to pyramids

My first introduction to working in Egypt was a project in Cairo's historic old quarter, following the 1992 earthquake that caused widespread and devastating damage. Cintec International won the contract to repair and reinforce a number of badly affected structures, with work commencing in 1998. The project consisted of some 15 notable mosques and maqaads, successfully strengthened using Cintec's patented anchoring systems. Most of the essential work was completed by early 2005, with ongoing localised repairs still being undertaken as and when required.

Following our successful work in the old quarter, we undertook several interesting and challenging projects before we embarked on our first pyramid restoration project; strengthening parts of the connecting corridors of the Red Pyramid's burial chamber. The Red Pyramid is the third largest of Egypt's pyramids, and was the first "true" pyramid built by Pharaoh Sneferu. Sneferu had built two previous pyramids, but these were not of a true triangular shape, and for structural reasons were not chosen by the Pharaoh as his final resting place. The work on the Red Pyramid was confined to strengthening the granite slabs immediately above the burial chamber's corridor.

### A LARGE PORTION OF THE BURIAL CHAMBER CEILING HAD COLLAPSED



### The Step Pyramid

Cintec's next project, the Step Pyramid, required careful planning and execution due to the very dangerous condition of the burial chamber ceiling. Again due to the 1992 earthquake, a large portion of the burial chamber ceiling had collapsed, depositing many tons of stone on to the base of the shaft 29 metres below. The resultant dome-shaped void exposed a ragged hanging inverted group of large and small stones, set in mud, measuring 8 metres by 8 metres. This was liable to collapse at any time.

The problem was that standard solid propping of the ceiling using scaffolding

could not be used, due to the haphazard interlocking of the fallen stones. Any upward point loading on a key locking stone could be the mechanism to release another 50 tons of stone on to an unsuspecting technician. However, Cintec had a product available that could be used to support the ceiling: water-filled blast mitigation devices known as WaterWall. The internally-reinforced PVC product can be inflated with air and then filled with water, and was originally developed by Cintec to produce shapes that are able to suppress improvised explosive devices. It was this product that was used to support the inverted dome of stone.





↑ Installation of WaterWall in burial chamber

← 1992 earthquake causes the Step Pyramid's burial chamber to collapse

As the WaterWall air bags are made to expand to specific dimensions, Cintec were able to design and fit the units in strategic positions around the chamber, to merely kiss the hanging stones without any upward thrust. The temporary support of the ceiling has now been finished, with the final pointing, grouting and anchoring processes approximately 50% complete.

It was on one of my visits to the Step Pyramid that I was asked my opinion on securing the remaining outer cladding of the Bent Pyramid, another construction by Pharaoh Sneferu, located 40 kilometres south of Cairo. The pyramid's top section sits at a slightly different angle to the main body, giving the structure its "bent" appearance.

### The Bent Pyramid

Before any structural restoration work is reconsidered, the exact nature of the pyramid's defects must be established, so that the correct intervention can be carried out. From a visual inspection, the structure shows distress along all the extremities.

What are the clues? The pyramid does not appear to have any foundation movement. All the missing cladding appears at interfaces or change of direction at the angles and between the ground and the cladding.

A popular theory is that the missing cladding was removed by local opportunist thieves. At the lowest levels that could be the answer, but at high level and in such random manner, with no sign of indentations of temporary scaffolding or of any symmetrical cutting of the blocks to aid removal, it does not seem likely or possible. It would have been extremely dangerous work. To dismantle a structure you normally need as much scaffolding as you would to build it, and opportunist thieves would hardly have sufficient resources. Indeed, if they merely wanted rough stones they could have found them in the hills adjacent to the centre of Cairo, without the trouble of removing and transporting them 30 miles out of town. The damage here appears to be caused by a giant whose hand has swept across the face of the pyramid with enormous energy, sucking out the facing leaving the ragged empty sockets.

### Thermal movement

In the case of the Bent Pyramid, and I believe in the case of all pyramids, the outer casing

has been affected by thermal movement.

Fortunately, the Bent Pyramid is the only pyramid with any degree of stone casing still attached, making the mechanism of failure apparent. The failure of all the perimeter edges show that the outer casing has expanded from the centre outwards, and movement has taken place on all of the extremities.

During the day the temperature rises to 40 degrees across the face of the outer casing, then at night cools to 3 degrees because of the lack of cover and exposure to the prevailing winds. This gives an average daily temperature fluctuation of 37 degrees. Obviously, this varies through the seasons, but to illustrate my point I will build these into the calculations that follow.

### Crunching the numbers

Limestone has a coefficient of thermal expansion of  $8 \times 10^{-6}$ , proportional to the change of temperature and to the original dimensions. Many natural stones, including limestone, retain a minute proportion of the expansion when they cool down and do not return to their original size.

Let us work on the calculation that of  $8 \times 10^{-6} \times (40-3) \times 100\text{m run} = 0.0296\text{m}$  of movement per 100 metres run in all



directions. However, this is also dependant on the size of the gaps between each stone. All movement from the thermal expansion of the casing would be taken up initially in the joints, but significantly the limestone does not go back to its original position. The expansion would create dust and stone particles that would detach from the stones, filling the voids and gaps between them. This would reduce the amount of contraction possible at night, in addition to the stones' natural propensity not to return to their original dimensions and position, and so the cycle would start again. Multiply this endless movement by the number of days the pyramid has been erected and you have the reason why all the outer casing has moved to the extremities, where it has buckled or displaced against blocks moving in the opposite direction, and then fallen off. It may then have been picked up by opportunists and removed from the site. I believe that this process is the mechanism of failure on this and all the other pyramids.

I have read that the original dimensions recorded by Flinders Petrie were inaccurate, and that the dimension taken in 2004 was larger by a small degree. This is what I would expect of a structure that is still moving and increasing in size. Furthermore, the convex shape of the pyramid's outer casing could be caused by the stones arching between fixed points. The transit of the sun across the region will vary over the seasons, heating one side more than another, giving rise to disproportionate movement particularly at the extremities.

↑ An 11 degree change in angle gives the pyramid its bent appearance

## THE OUTER CASING HAS BEEN AFFECTED BY THERMAL MOVEMENT



↑ Crumbling casing on the Bent Pyramid's outer corner

### Learning from the past

Another important question to consider is this: Why does the Bent Pyramid still has half of its outer casing attached, when the Red Pyramid and the Great Pyramids at Giza plateau have virtually none?

I believe this was due to the increased skills of the craftsmen, who developed more knowledge and precision as the process of pyramid construction developed. They became able to provide better accuracy, build quality and jointing of the slabs. It is likely that the Bent Pyramid was built with less care and with more voids between the stones that acted like expansion joints. The casing blocks being included inwards at the base of the pyramid may have limited the expansion.

Finally, could the sight of the progressive damage to the outer edges of the pyramids (that would have taken place relatively soon after their construction) be the reason that having spent so much time and energy constructing these wonderful monuments, the Egyptians altered their burial method to that seen at the Valley of the Kings?

### Author biography

After over 20 years in heavy engineering, maintenance and restoration, Peter James started Cintec International in 1984. Cintec develops patented sock reinforcement anchoring systems for retrofit use, winning the Queen's Award for Innovation (2002) for strengthening masonry arch bridges. Today Cintec operates across the UK, America, Canada, Australia, India, North Africa and the Middle East.