Project Summary – Pre-stressed Stone Staircases: Do They Explode?

Pre-stressing as a technique is generally well understood as it has been used for many decades to improve structural performance, particularly of concrete and man-made masonry. Pre-stressing natural stone for staircases specifically, however, has only been done in recent years and so some specific aspects of stone behaviour under pre-stress are less well understood. Pre-stressed stone staircases are becoming increasingly popular among architects and clients as they make efficient use of materials and look very elegant, so Price and Myers, a structural engineering firm based in London, approached the Engineering Department to request some research into two aspects of stone behaviour under prestress:

1. The effect of bedding plane orientation on failure behaviour
2. The effect of edge distance on failure behaviour, where edge distance is defined as the distance between the edge of a pre-stressing tendon and the edge of the stair tread

These two aspects were studied for three types of limestone through theoretical modelling and experimental testing. Experimental data were used to verify whether certain models of behaviour could be used to predict failure behaviour and make design easier in the future.

How do Pre-stressed Stone Staircases Work?

Figure 1: A pre-stressed stone staircase

A pre-stressed stone staircase is made up of a series of treads cut from individual blocks of stone. Holes are drilled through the treads and the flight is assembled on temporary block work; then a tendon threaded through the holes (the bottom left of figure 1 shows the tendon). The tendon is tensioned from both ends to push the treads together so that the staircase can support its own self weight as well as any imposed loads. Finally, the blockwork is removed so that the staircase is free-standing.

Bedding Plane Orientation

^ Figure 2: Compression testing

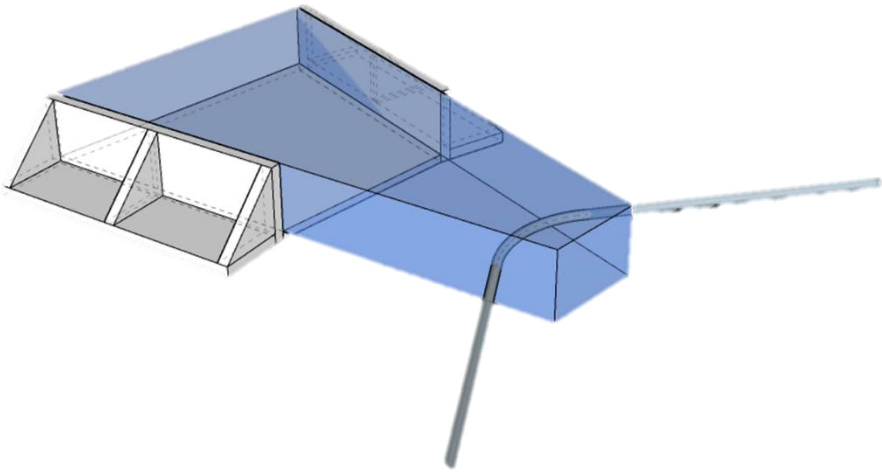
Limestone is a sedimentary rock and so is composed of strong and weak layers of carbonate grains and shell fragments. It is though that stone is strongest when the bedding planes are perpendicular to the loading direction and weakest when they are parallel. For this reason, pre-stressing parallel to the bedding plane direction has so far been avoided. However, this restriction is based on instinct rather than scientific findings.

To investigate whether bedding plane orientation does affect stone strength, cuboidal samples were tested in compression (figure 2) with bedding planes orientated either parallel or perpendicular to the loading direction to see whether orientation affects strength.

For some types of limestone strength was found to be independent of orientation, but this was not universally the case. Therefore, it is important to design using the strength associated with the weakest orientation so as not to overestimate the stone's strength.

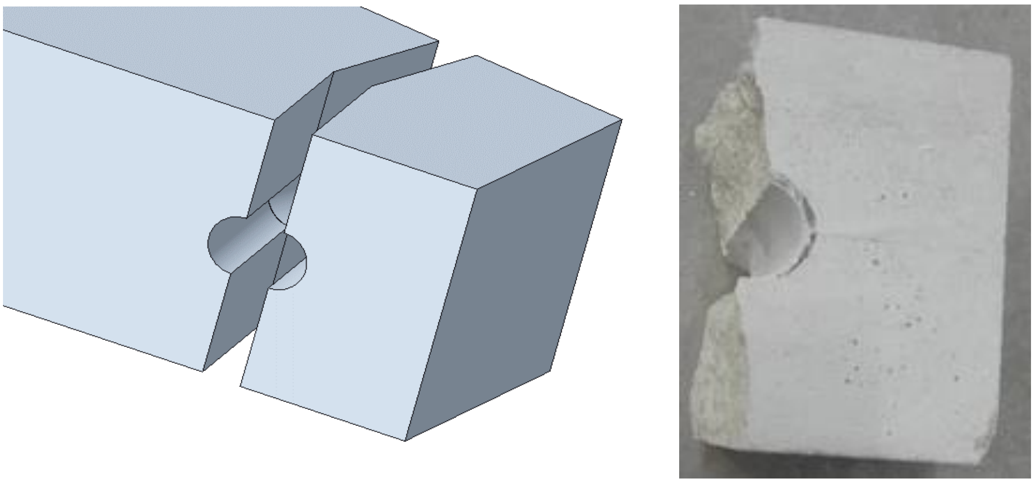
Edge Distance

It was also though that if the distance between the tendon and the edge of the stair tread is too small, the tendon could cut through the tread in a sudden brittle failure. To see whether this was the case, and to try find theoretical models that could be used to predict failure, wedge-shaped stone samples were threaded with a steel tendon which was tensioned from both ends until the stone failed (figure 3). This was to simulate the load on an individual tread within a staircase.



^ Figure 3: Edge Distance Testing

When the edge distance is large, failure was thought to follow a simple behavioural model where the tread breaks along the line of the tendon in a vertical plane. Failure load can be calculated assuming load is equal to the average stress on the failure plane multiplied by the failure plane area. Testing samples with an edge distance of 50 mm revealed that this model of failure was correct – the shape of the broken treads matched what was expected (figure 4) and the failure load predictions matched the test data well.



^Figure 4: Comparison between model and test sample for 50 mm edge distance

At small edge distances, the sample becomes more difficult to analyse as a complex three-dimensional stress state exists in the region ahead of the tendon hole. Testing samples with an edge distance of 25 mm showed that failure is much more complex and varied with two sub-types of failure observed (figure 5). This made it difficult to find a model to fully explain behaviour. Despite this, a simple model was found, based on general principals of behaviour, that could be used as an initial estimate of when failure might occur.

^ Figure 5: The two types of failure observed when edge distance was 25 mm

Future Work

Due to time and funding limitations, only a few samples were tested during the project. A lot more testing could be done in future on different tread geometries, edge distances and types of stone to see whether the models developed during the project are more widely applicable or whether they need further development to be more useful for design.

This was a very exciting project to be involved with as my results will be used by a structural engineering firm to help them with design work in future. I worked in an area in which there has been very little research in the past, so even though there is still much to do, the work I have done provides the initial building blocks for future work. Structural engineering is a very exciting discipline to pursue a career in as it impossible not to see applications of structural engineering around us in our daily lives.