The effect of impact angle and bond strength on fragmentation in laminated materials

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Abstract. An experimental study was undertaken to explore the effects of weak laminations on the fragmentation of impacting rocks. In this work, the fragmentation behavior of manufactured disc specimens of laminated travertine marble is described according to variations in the lamination bond strength, the orientation of laminations at impact, and the impact energy. An experimental apparatus and procedure were developed so that the discs, 96mm in diameter and 25mm thick, could be impacted neatly on their circumferential edge, at a selected lamination impact angle, and subject to filming with a high speed camera. The results of the study generally indicated that weaker bonds cause fragmentation from lower drop heights, as expected. However, the results also indicate that the critical height for breakage is relatively lower and insensitive to the impact angle when the laminations are between 45 and 90 degrees relative to the impacting surface, but the critical height for breakage increases significantly (by a factor of between 2 and 4) as the orientation of the laminations becomes parallel to the impact surface. The presence of laminations and their orientation to the impact surface, directly influenced the failure mechanism of specimens upon impact. At low lamination impact angles, failure was by parting along laminations in direct tension (reflected compression). At intermediate impact angles (approximately 45 degrees), the fragmentation of the specimens was more explosive and fractures were a combination of steps across stronger sheets, and splits along weaker bonded laminations. For high impact angles, fragmentation occurred in indirect tension, along weak laminations.

1. Introduction

There are many rocks that contain naturally occurring weaknesses, such as sedimentary laminations, metamorphic cleavages and foliations, bonded joints or clay-filled seams. These are known to affect the directional strength of rocks [3,4,5] and consequently they also influence the fragmentation of such rocks on impact [1,2].

Risks to life and property posed by rockfall are managed by on the basis of their energy, estimated from modelled trajectories of likely falling blocks. The reliability of modelled trajectories and energies is strongly influenced by the assumed size of a falling rock, but this can change greatly if fragmentation occurs upon impact during the rockfall event.

The impact energy of a falling rock depends both on its mass and its velocity. Rocks which breakup on impact as they fall have reduced energy through their reduced mass, so inability to predict fragmentation leads to overprediction of block energy. However, as energy depends on the square of the
velocity, the potential also exists for small fragments to be ejected with high speed and energy during fragmentation of a large block, which requires very different management strategies than would be needed for the unbroken block.

2. Approach
This project dropped discs of laminated rock material onto a concrete surface to impact with the laminations at different angles to the impact surface (0°, 22.5°, 45°, 67.5° and 90°). To isolate the influence of the laminations, the specimens were all manufactured to be identically composed of stronger, thick layers, bonded together with a thinner, weaker material. The requirements for the stronger layers were that they:

- be natural rock;
- be of consistent thickness and consistent surface properties;
- have consistent material strength; and
- be relatively easy to cut and shape.

Travertine limestone/marble was selected as the material, and a quantity of 475mm x 475mm tiles with a thickness of 12mm were sourced. These had smooth, honed surfaces, and being essentially composed of calcite, they were relatively easy to cut.

To bond the travertine sheets together, a series of builders’ plasters and cements, with a variety of strengths and hardnesses, were sourced. These included:

- plaster of Paris,
- softwall plaster,
- hardwall plaster (“base coat”),
- cornice cement, dental plaster and
- Portland cement.

The strength of the various bonding agents (σb) was quantified by indirect tensile testing of 25mm thick, 96mm diameter, cast discs of each material. Similar sized samples of travertine were also cut and tested for their indirect tensile strength (σt), so that the relative strength of each bonding material could be expressed as the ratio of the indirect tensile strengths (σb/σt). Ratios ranged from 0.3 (for soft plaster) to 1.0 (Portland cement).

To facilitate testing that could compare the importance of impact angle, with all other factors being equal, disc shaped specimens were created, and dropped to achieve continuous impact along an outer edge. The manufacturing process involved laminating nine 120mm x 120mm squares of 12mm travertine together with 1mm bonding layers to form a 116mm high stack of layers (figure 1, left). These were then cored with a 100mm diameter diatube to give a 120mm high, 96mm diameter, cylinder of laminated sample, which was subsequently cut into 25mm thick slices to form the test specimens (fig.1, right).

In order to ensure that dropped specimens impacted neatly along a circumferential edge, the method adopted involved dropping the specimens from a gently inclined (~1° from vertical) polished stainless-steel surface, suspended above a correspondingly inclined concrete impact slab (figures 2a and 2b). The surface was discontinued 150mm above the impact slab so that the specimen was free (clear of any contact with the surface) at the point of impact (figure 2b). Illumination ensured good quality high speed images could be acquired (figure 2c). When gently released from a position directly in contact with the surface, the specimen could fall whilst guided in its fall direction by the surface (figure 2c) to make even, simultaneous contact with the impact slab along its outer edge (figure 2e).
Figure 1. Laminated stack of travertine sheets (bonded with plaster of Paris) showing cutting and coring lines (left); laminated specimen (bonded with Portland cement) showing impact angle (right).

Figure 2. Testing arrangement: a) polished stainless steel guide surface, above impact slab; b) impact slab below guide surface showing tilt to achieve perpendicular impact; c) illumination arrangement for high speed photography; d) high speed image of disc in motion during a test; e) high speed image of a disc impacting during a test.
For each combination of bond strength and impact angle, the following procedure (illustrated in fig. 3) was adopted to find the critical drop height at failure from 4 available specimens. This approach allowed the critical height to be found by repeated dropping of the first 3 specimens, and confirmed by a single drop of the 4th specimen.

The testing procedure for each combination of defect strength and impact angle was:

- Specimen 1 was dropped from incrementally increasing heights of 0.15, 0.3m, 0.45m … until it fractured.
- Specimen 2 was then dropped from increasing increments of 0.075m, starting from 0.075m higher than the highest position that did not break Specimen 1, until it fractured.
- Specimen 3 was then dropped from increasing increments of 0.038m, starting from 0.038m higher than the highest position that did not break Specimen 2, until it fractured.
- Specimen 4 was then dropped from the same height of Specimen 3, to confirm the result.

The final 150mm of the fall was recorded by high speed camera from two directions.

3. Results
The indirect tensile strengths determined from the Brazilian tests are presented in figure 4.

The discs of solid travertine and cement paste returned similar high strengths, and the discs of the other bonding agents returned a range of lower strengths. Note that a result for the softwall plaster is not shown as reliable discs of this material could not be produced for testing due to the amount of shrinkage that occurred in the drying of a large thickness of this material.

The results of the critical fragmentation heights determined from the drop tests are shown in figure 5. The intact, un-laminated travertine could not be broken when dropped from the available height of 3.5m.
Figure 4. Brazilian Indirect Tensile Test results

Figure 5. Plot of critical fragmentation heights with respect to bond strengths and impact orientation.
In general, all of the laminated samples fragmented at drop heights less than 2m, except for the Portland cement bonded specimens ($\sigma_b/\sigma_t=1.0$) dropped with their laminations parallel to the impact surface, which could not be broken from the maximum height of 3.5m. It is interesting that the Portland cement bonded specimens fragmented at all other impact angles, despite the indirect tensile strength of the Portland cement paste itself being equal to that of the travertine. This suggests that the tensile strength of the bonding material itself may not be a good measure of the strength of the bond it forms with a different material.

Generally, bonds using weaker materials resulted in fragmentation from lower heights. Greater energy (drop height) was also needed to break specimens at lower impact angles (laminations parallel to impact surface). The difference was generally a factor of between 2 and 4 from low to intermediate impact angles ($\alpha<45^\circ$). There was little difference in breakage heights between intermediate and high impact angles ($\alpha>45^\circ$).

It was observed that the fracture mode varied with impact angle, and to a lesser extent, with bond strength. Whilst both low and high angle impacts each resulted in a planar failure, impacts at low angle failed by delamination of an outer layer along the bond through direct tension (reflected compression) whereas high angle impacts tended to cause failure through indirect tension across the bonds in the centre of the specimen (as shown in figure 5). Impacts at between 22 and 45° tended to cause a wedge failure where an outer lamination separated but in multiple fragments. Impacts at 45° in strongly bonded materials displayed stepped failure that fractured along bond and across travertine sheets.

fig. 5 shows that despite releasing the specimens with their laminations at 5 selected angles (0°, 22.5°, 45°, 67.5° and 90°) they impacted at a wider range of angles, reflecting a tendency to rotate slightly during their fall. This occurred despite making great efforts to release the discs without inducing any rotation. A more consistent method of release is needed. It was also noted that for higher release positions (above 2m) there was a tendency for the discs to separate from the inclined surface before impact, leading to impact at a single point, on the edge of one face. This is considered to occur as the result of the Bernoulli effect whereby reduced pressure on the outer face of the disc, due to the air rushing over it as it falls, causes the disc to be sucked away from the guide surface. The presence of an upper bounding surface (perhaps a Perspex sheet) would reduce this effect.

4. Conclusions
The likelihood of a falling block to fragment at impact as it falls was demonstrated to depend most strongly on the strength of the defect, however, a significant dependence on the impact angle (angle between the defect and the impact surface) was also demonstrated. Generally, for a given bond strength, the critical height to cause fragmentation decreases as the impact angle increases. The project was successful as a pilot study, but refinements can lead to improved results.

References
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