

Effect of element orientation on concrete breakout capacity and crack propagation in anchor-bolt pull-out using the mesh fragmentation technique

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ABSTRACT

The numerical prediction of concrete breakout in post-installed anchors depends on how potential crack paths are represented. This study evaluates the influence of element orientation in the mesh fragmentation technique on pull-out strength, crack trajectory, and post-peak response. A two-dimensional plane-strain model was developed in ANSYS and compared with a published adhesive-anchor pull-out test involving concrete with a compressive strength of 30 MPa and an embedment depth of 60 mm. Concrete was represented by the Menetrey-Willam model; zero-thickness cohesive interfaces and contact were assigned between fragmented elements. Four meshes-regular quadrilateral, triangular antiparallel, triangular parallel, and randomly oriented triangular-were compared with a continuous finite element model. A preprocessing algorithm identified internal edges, duplicated shared nodes, and generated interface pairs automatically. The quadrilateral and antiparallel meshes overpredicted peak load by about 37% and 17.5%, respectively, and produced stepped crack paths. The parallel mesh predicted peak load within 2% but softened more rapidly than the test. The random mesh produced the closest overall response: peak-load error below 1%, a comparable descending branch, and a crack angle of approximately 33.9°, compared with 32° in the experiment. The continuous model overpredicted capacity by about 42%. These findings show that interface orientation substantially affects both strength and fracture geometry in fragmented meshes. Randomly oriented interfaces improved agreement for this anchor configuration, although the plane-strain idealization limits direct transfer of the findings to three-dimensional anchors.

KEYWORDS

Mesh fragmentation technique, adhesive anchor, concrete breakout, cohesive zone model, crack propagation.

1. Introduction

Post-installed anchors transfer tensile forces to concrete through bond and confinement. Their failure can involve localized cracking and concrete breakout, which makes the calculated capacity sensitive to the representation of discontinuities. In a fragmented mesh, adjacent solid elements are connected by cohesive interfaces; the available crack directions therefore follow element boundaries. Earlier studies characterized adhesive-anchor behavior [1], assessed cohesive traction-separation laws [2], developed adaptive interface-based crack models [3], and represented concrete fracture with mesoscale interfaces [4]. Nevertheless, the independent influence of mesh orientation on predicted anchor pull-out response requires explicit comparison. This work compares four fragmented meshes and a continuous

model against the same test, with emphasis on strength, post-peak softening, and breakout geometry.

2. Methodology

The reference test reported by Eligehausen et al. [1] used an adhesive anchor with a 60 mm embedment depth in concrete of 30 MPa compressive strength. The specimen was represented in ANSYS Mechanical APDL 2024 R2 under plane strain and displacement-controlled tensile loading. Concrete followed the Menetrey-Willam yield surface, while steel was modelled with a von Mises plasticity law and isotropic hardening. Bilinear cohesive traction-separation behavior and Coulomb contact described internal concrete interfaces and the anchor interface. The concrete tensile strength and mode-I fracture energy were 3 MPa and 0.134 N/mm, respectively, as specified in the source model.

An automated preprocessing routine read element connectivity, found each shared internal edge, duplicated nodes to release direct kinematic continuity, created one target-contact pair per interface, and assigned the cohesive law. The four meshes comprised axis-aligned quadrilaterals, triangular elements with dominant orientations opposing or following the expected crack trajectory, and randomly oriented triangles. Material properties, interface parameters, boundary conditions, and loading were held fixed across the fragmented models. A conventional continuous model supplied a comparison without explicit interelement cracks.

Before analyzing the anchor, the constitutive response was checked against the concrete tension and compression curves and the steel stress-strain response reported in the article. Separate interface tests under normal opening and tangential sliding were used to check the bilinear cohesive laws and their fracture-energy dissipation. The preprocessing routine was also checked geometrically: duplicate nodes retained coincident coordinates, each interior edge received one cohesive contact pair, exterior edges remained intact, and boundary constraints were reassigned after node duplication. With interface damage suppressed and sufficiently high interface stiffness, the fragmented model reproduced the elastic response of its continuous counterpart. These checks separate errors in interface generation from differences attributable to orientation during the pull-out simulations.

The model comparison was designed to isolate the orientation effect among triangular discretizations. The regular positive- and negative-orientation layouts differ in their alignment with the expected diagonal fracture, while the irregular triangular layout has no preferred direction. The quadrilateral configuration tests a common

structured mesh and the continuous configuration tests the consequence of omitting explicit internal separation. Thus the five curves in Figure 1a are interpreted jointly with the crack patterns rather than by their peak loads alone. The analysis is two-dimensional: the out-of-plane strain is constrained and the three-dimensional geometry of a complete anchor breakout cone is represented only approximately.

3. Results and Discussion

Figure 1(a) compares load-displacement curves with the experimental response [1]. The regular quadrilateral and antiparallel meshes overestimated peak load by approximately 37% and 17.5%. The aligned triangular mesh matched the peak within 2%, but its post-peak load decreased too sharply. The randomly oriented mesh matched peak strength within 1% and followed the experimental descending branch more closely. The continuous model exceeded the measured peak by approximately 42%, indicating a broad rather than localized damage region in this simulation.

Figure 1(b) reproduces the Randomly Oriented Triangular Mesh failure pattern. Its predicted crack inclination of about 33.9° is close to the measured 32° . By comparison, the source article reports approximately 19° for the quadrilateral mesh, 24.6° for the aligned triangular mesh, and 15° for the continuous model. The stepped trajectory of the structured meshes reflects the restriction of separation to prescribed element edges. The random interface network provides a wider choice of local crack directions and better reproduces the breakout cone. These observations concern one specimen and one calibration; mesh randomness alone does not establish general mesh independence.

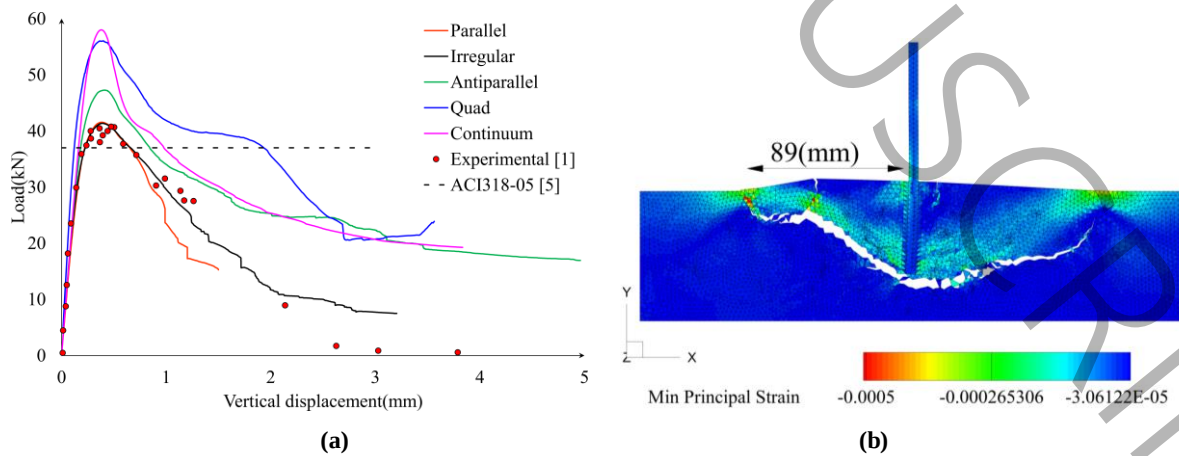


Figure 1. (a) Pull-out load-displacement response of the experiment and numerical meshes; (b) concrete breakout pattern for the Randomly Oriented Triangular Mesh

The load curves also show why a strength-only validation is insufficient. Two models may have similar maxima while predicting different rates of unloading after cracking begins. A steep post-peak branch implies that the numerical model releases its load capacity over a short displacement range. In the aligned mesh, a connected set of favorable interface directions allows a comparatively direct separation path. The random mesh requires the opening and sliding response to develop over interfaces with different orientations; the resulting global response more closely follows the measured decline. This comparison does not isolate individual cohesive parameters, since their values were held constant; it assesses how one prescribed interface law interacts with alternative mesh geometries.

The fracture pattern provides an additional measure of accuracy. The random mesh predicted a breakout angle of approximately 33.9° , close to the experimental 32° and consistent with the inclined breakout mechanism considered in ACI 318-05 [5]. In the continuous model, plastic strain spreads across a wider area and produces a shallower apparent cone. Taken together, peak force, post-peak response, and fracture inclination make a stronger case for the random layout in this case than any single quantity alone. Because the study concerns one concrete strength, one embedment, and one anchor geometry, further testing should vary these conditions before using the result as a general mesh selection rule.

The numerical procedure has an important practical implication for reproducibility. In a conventional continuous mesh, neighboring elements share nodes and a discrete displacement jump cannot form along their common edge. The fragmentation routine assigns separate node identifiers while preserving their original coordinates, then places a cohesive interaction on every interior edge. Hence a crack can initiate where the interface strength is reached and advance through progressive loss of cohesive traction. Edges on the outer boundary are excluded from fragmentation, and applied restraints and imposed displacements are transferred to the appropriate new nodes. Checking that each interior edge appears once prevents duplicate contact pairs, which would otherwise add spurious resistance. These implementation choices make the comparison of geometries interpretable: differences in the response arise from accessible interface directions under the chosen model assumptions.

The findings should also be read in light of the governing simplifications. The plane-strain assumption constrains deformation normal to the model plane,

although the real anchor develops a spatial failure surface. The cohesive law prescribes the separation response, and its calibration influences the computed load and softening slope. Agreement for the irregular mesh in one validation specimen does not prove that every random triangulation will give the same prediction. Repeated realizations and systematic changes in element size would quantify the scatter attributable to the random layout. Three-dimensional simulations and tests with other embedment depths, edge distances, and concrete strengths would establish whether the same orientation trend persists under other restraint and fracture conditions. These tests are a logical next step for using fragmented meshes in anchor design studies.

4. Conclusions

Element orientation strongly affected the predicted concrete breakout response. Regular quadrilateral and antiparallel meshes developed constrained, stepped crack paths and overestimated capacity; the parallel mesh accurately captured the maximum load but produced excessive post-peak softening. The randomly oriented mesh simultaneously improved peak-load, post-peak, and crack-angle predictions for the investigated anchor. A three-dimensional study and additional anchor configurations are needed to examine how broadly this result applies.

5. References

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