RS3 Feasibility Modelling of a Semi-Circular Notched Sample Spalling Experiment

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Abstract. Spalling in rock has been an area of focus for researchers since it was first observed in tunnels and boreholes. The earliest form of spalling tests are in-situ tests, but due to high costs and the risks associated with allowing an excavation to fail, the focus of spalling research has shifted to a safe and controlled laboratory environment. Numerous tests exist today that can recreate the conditions for spalling with unique geometry and loading conditions. A review of currently established tests allows for gaps in the literature to be identified, ultimately leading to a new test. The Semi-Circular Notched Sample spalling test (SCNS test) was conceptualized as a rectangular specimen with a semi-circular notch at the mid-height. Due to the compression of a circular notched sample, a stress concentration is created, and compressive stresses at the notch are magnified. The condition for loading was analyzed in *RS3*, and a full-area compressive load was identified. Results from the modelling and physical testing are compared via strain results from the *RS3* simulation, and the strain gauges equipped on the physical test. Based on the comparison between numerical models and experimental data, the model predictions matched successfully with the physical samples. This indicates viability in the SCNS test's ability to re-create the spalling phenomena under the simplest of testing conditions.

Keywords: Spalling · RS3 · Laboratory Test · Sandstone · Elastic Continuum

1 Introduction

Numerous researchers have become interested in the spalling process since it was first observed to occur in tunnels and boreholes in highly stressed ground (Jacobsson et al. 2014). There have been attempts to study this process in in situ conditions, as well as recreating the conditions in a laboratory setting. In situ tests have been carried out on tunnels and pillars by numerous researchers (Martin et al. 1997; Liu et al. 2017; Martin and Maybee 2000), but these tests have proven to be expensive and challenging. To study the spalling process with less risk, and significantly fewer costs, the laboratory experiment has become the focus of spalling research. Physical experiments such as the popular Hole-in-Block test were created where under replicable conditions, a block with a hole in the center subjected to uniaxial, biaxial, or triaxial loading creates a spalling condition in the hole (Carter 1992; Martin et al. 1994; Haimson 2007; Gong et al. 2019;

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Si et al. 2020). Other tests such as the Hollow Cylinder test (Daemen and Fairhurst 1970), Bending of an Axially Compressed Beam (Cho et al. 2009), Surface Instability Apparatus test (Kao et al. 2011), Eccentric Uniaxial Compression (Pinto and Fonseca 2013), and the Uniaxial Compression of a Notched Sample (Jacobsson et al. 2014) have been created as alternatives to the Hole-in-Block test with each test having its strengths and limitations.

Established spalling experiments are already known to exist, but the question arises as to whether any of the existing methods can be improved upon. With a trend in lowering costs and increasing ease of testing, the Semi-Circular Notched Sample spalling test (SCNS test) was conceptualized to reduce the sample size, and effectively lowering the required load to initiate spalling. A test that can accommodate spalling at relatively low loads under a simple loading condition has not yet been identified, and thus a feasibility study was undertaken to determine if such a test has viability through preliminary numerical modeling and experimental results. The objective of the study is to develop a test that demonstrates the mechanisms of spalling at a lower cost by using uniaxial loading at a lower peak load, and a smaller, simpler sample geometry compared to other tests. The SCNS test aims to achieve a better stress concentration around the notch that presents spalling over other types of failure, as can be seen in other types of tests (Hole-in-Block). Reproducibility is key for the SCNS test as its goal is to serve as an initial step in the viability of other larger experiments that will utilize the same testing procedure in different rock types and geometries. This study will directly compare the proposed test using 3D numerical models created in *RS3* (Rocscience 2022) with physical experiments to examine its feasibility. The conceptualized test should meet the stated criteria for its geometry and loading conditions to be reproducible in labs that may not have large loading frames capable of complex loading conditions. It is important to note that the SCNS test is not representative of a tunnel, but of the spalling mechanisms found within a rock.

2 Numerical Modelling

RS3 was used to create 3D finite element elastic continuum models to identify a sample geometry and loading condition that can produce the desired outcome. To verify the dimensions of the sample, and to ensure the correct loading condition was selected, distributions of stress magnitude and position were considered. The results of the models were then used to ensure that high compressive stresses existed at the notch, while maintaining levels of tensile stress below the expected tensile strength.

2.1 Model Geometry

Numerical models in 3D were created using *RS3* (Rocscience 2022) to verify the dimensions and loading conditions of the SCNS test. Model dimensions were first determined by using a certain number of notch radii as the sample's height, width, and depth. The sample dimensions are selected so that the stresses from the loading frame can be distributed evenly along the sample without any major effects being imposed by the loading frame. The radius of the notch is expected to be 3.6 cm based on available drill core

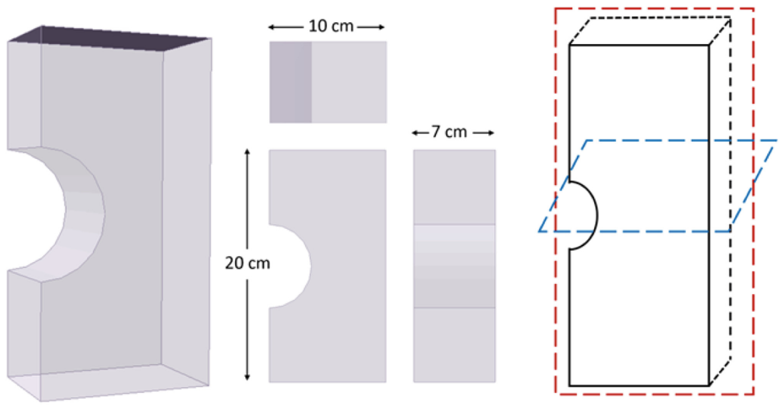

Fig. 1. 3D dimension of proposed SCNS geometry and planes of interest for analysis

barrels which results in initial model dimensions of 21.6 cm high, 10.8 cm wide, and 10.8 cm deep. Carter, 1992, describes the effects of buckling and indicates a width-to-height ratio of 1/3 is sufficient to prevent out-of-plane buckling within an axially compressed sample. Applying the ratio described by Carter 1992 to our sample geometry provides confidence that buckling failure is unlikely to occur given the selected geometry. The sample dimensions are simplified to the nearest whole number for ease of ordering the product. This results in a final proposed geometry for the SCNS test of 20 cm high, 10 cm wide, 7 cm deep, and a 3.6 cm radius circular notch as illustrated in Fig. 1.

2.2 Intact Rock Parameters and Modeling Methodology

The rock to be tested is Wallace Sandstone sourced from Wallace Quarries in Nova Scotia. The Wallace Sandstone is a relatively homogeneous rock from the Cumberland group of the late carboniferous Boss Point formation (Ghasemi and Corkum 2022). This sandstone has elastic and strength properties illustrated in Table 1 that are used for numerical simulation. Knowing the rock mass characteristics gives an initial estimate that spalling should happen at around 120 MPa around the notch according to Martin et al. (1994) estimates. The sample geometry was first generated by creating a block of the desired size (20 × 10 × 7 cm), and then removing or "excavating" a semi-circular notch (3.6 cm radius) from the samples mid-height. The boundary conditions consist of a load type, a normal stress restraint, and free surfaces. The top surface was subjected to a loading type, either an applied stress or displacement boundary. The bottom surface of the sample has a normal stress restraint which provides stress equal and opposite to the force applied normal to that plane, simulating the bottom platen of a loading frame. All sides of the samples were assigned free surfaces. The mesh has a uniform density of 5 mm triangular elements throughout the entirety of the sample with approximately 60,000 elements. The model was run using elastic conditions to assess stress concentrations due to the notched sample geometry. Throughout modelling of the SCNS test, boundary conditions and mesh element sizes were kept constant to produce comparable results.

Table 1. Numerical Model Material Properties

Young's Modulus	Poisson's ratio	UCS	Tensile Strength
30 GPa	0.15	80 MPa	8 MPa

2.3 SCNS Model Results to Assess Loading Condition

Three model scenarios were created for the SCNS test. A full area and half area load were used to determine the best loading condition for the test. A displacement load model was then created to verify the selected stress load model as the desired loading condition. Stress and displacement load types were used to verify the stress redistributions within the sample, since each load type has a different reaction to the bending moment. The loading conditions in the full area model consist of a 30 MPa stress load applied to the sample's top plane. This load type illustrates a load described by Cho et al. (2009) where bending and compressive forces are generated within the samples body. Bending is generated due to the notch while compressive forces are generated due to the axial load acting along the entire surface. This load type generates enough stress within the sample to exceed the anticipated spalling stress level at the notch while ensuring there is no anticipated tensile failure at the opposite boundary. The loading conditions for the half-area model are like that of the full-area model. A 30 MPa stress load is applied, but the load is only distributed across half of the sample's top surface starting at the notched edge and finishing at the sample's center. This eccentric loading condition described by Pinto and Fonseca (2013) produces a bending moment to intensify the compressive stress magnitudes at the notch. This load type generates enough compressive stress at the notch to produce spalling but also had significant tensile stresses generated at the boundary opposite the notch. Such tensile stress is larger than the tensile strength of the Wallace Sandstone and thus, it's a concern that loading in this configuration would cause the sample to fail in tension rather than by spalling. To verify the full area load, a seven-stage displacement load model is created. The displacements were applied in 0.1 mm increments until a range that generates similar stresses at the notch as the stress load types were obtained. Further increments of 0.01 mm displacements were placed within such range until comparable results were obtained. At a displacement of −0.325 mm, similar stress levels were observed to be comparable to the stress loading results. The summary of the maximum stress encountered from each loading condition is shown in Table 2. Figure 2 illustrates the distribution of the stresses within each model.

3 SCNS Laboratory Experimental Tests

The feasibility study was undergone to determine if the proposed geometry and loading conditions were able to recreate the spalling phenomenon. Two SCNS samples were prepared and loaded using a 2 MN Instron uniaxial loading frame. One sample was equipped with three strain gauges to compare the physical testing results to the simulated test.

Table 2. SCNS Modelling Results

	Applied Force (kN)	σ_1 at notch (MPa)	σ_3 at notch (MPa)	σ_1 at boundary (MPa)	σ_3 at boundary (MPa)
Full-area stress load	210	152.4	9.4	0.3	−16.1
Full-area displacement load	–	156.2	9.1	46.3	−1.6
Half-area load	105	146.0	8.6	−0.3	−54.2

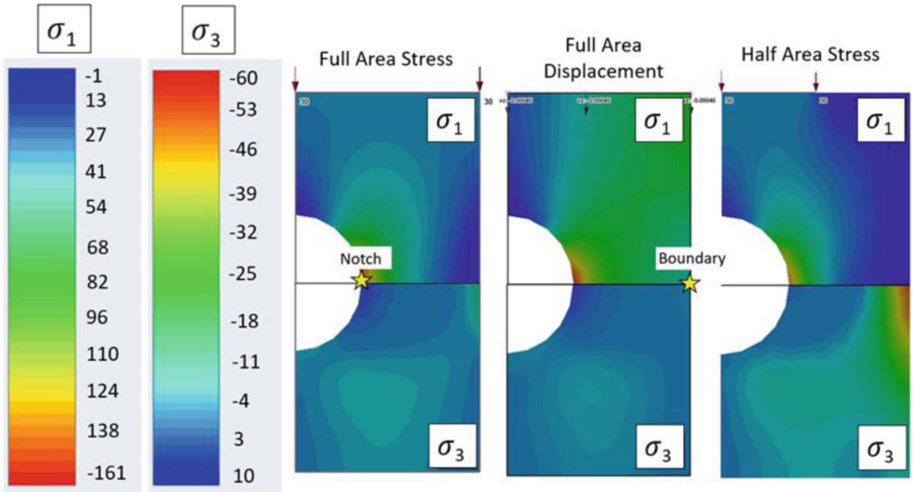

Fig. 2. RS3 σ_1 and σ_3 contours for full area stress load, full area displacement load, and half area stress load. Contours illustrate the maximum stress concentration where failure is expected to occur

3.1 Condition of Specimens Prior to Testing

The SCNS samples indicated no notable defects after preparation. The conditions of one sample before testing are shown in Fig. 3b. Three main things should be noted from the samples. The first is that there were punch-outs observed around the drillhole at the specimen's surface. The second is the color around and inside the notch which originates from excess glue during strain gauge installation. It is expected that excess glue will not influence the results of the test. Lastly, some of the sample's corners were chipped during the preparation and transportation of the samples. As they are located away from the notch, no major effect is expected from them. Strain gauges were installed on only one of the SCNS samples and were selected to be able to indirectly monitor stress distributions in the sample as it was being loaded. The configuration and location of the strain gauges can be seen in Fig. 3a.

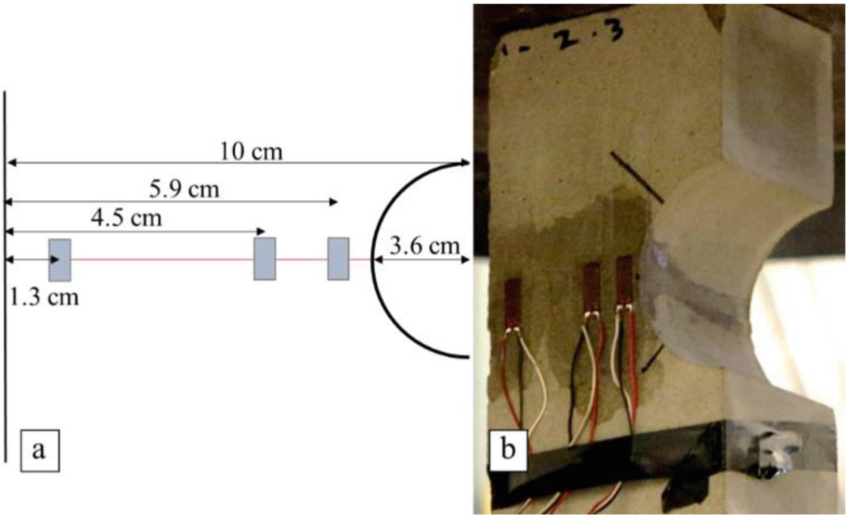

Fig. 3. SCNS sample strain gauge configuration a) Dimensions b) Actual sample

3.2 SCNS Test Results

SCNS test 1 had spalling in the notch before the ultimate failure was reached. Spalling started at a load of 213 kN. It fully developed and the entire notch spalled at a load of 216 kN. At this point, there was some failure in the top left corner. After spalling fully developed, the load slightly decreased to 210 kN where the sudden failure of the sample was experienced. The ultimate failure was due to the connection of a crack between the failed corner and the notch formed by spalling. Figure 4a shows the failed sample after it is pieced back together.

SCNS test 2 also ultimately failed by spalling inside the notch. However, an early crack on the top towards the notch developed before spalling initiated at a load of 202 kN and caused a reduction of 3 kN in the sample. Spalling initiated at a load of 231 kN and fully developed at 240 kN. Just as in the previous test, this was the maximum load in the sample. The ultimate failure was at a load of 230 kN with a mechanism almost identical to the first test. Figure 4b is the reconstructed sample after failure. Table 3 is a summary of all the results of the tests. For all tests, the load, time, and displacement were constantly recorded using the DAQ (Data Acquisition System).

3.3 Strain Gauge Results

Strain gauges were applied to one of the SCNS samples to better understand how stress is distributed through it as it is getting loaded. The locations of the strain gauges are shown in Fig. 3a. This location is the middle axis of the sample where the highest stress and stress changes are expected. This measurement can be directly compared to the numerical modeling expected strains. Figure 5 is a comparison of the results from the test and the model. The trends are similar in that the strain is larger closer to the notch and is much smaller far from the notch. The strain gauges nearest to the notch provide

Table 3. SCNS test summary results

	SCNS 1	SCNS 2
Type of failure	Spalling	Spalling
Maximum Load (kN)	216	247
Maximum Stress at the Top (MPa)	30.7	34.8
Time to Failure (s)	249	246
Displacement to Failure (mm)	2.04	2.03

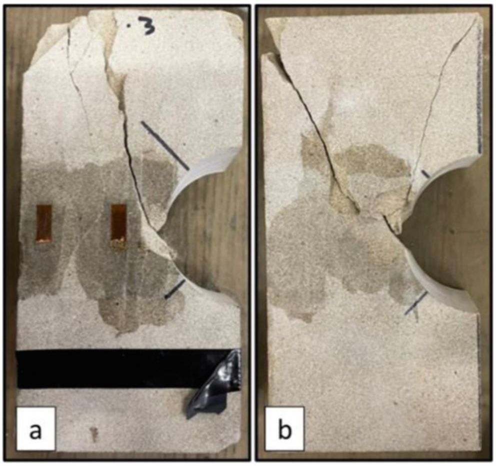

Fig. 4. SCNS test failed samples a) sample 1 b) sample 2

the closest match the actual measurements, while the farthest strain gauge gave the least similar values. This is most likely due to the propagation of the crack (observed at 180 kN load) that essentially divided the sample. As this fracture propagated it changed the load distribution making it harder to predict strains.

Another way to visualize these results is to plot the strain vs the distance from the notch. This plot is provided at different loading levels in Fig. 6. The strains at maximum load and 50% load are shown for the actual test and the numerical models. The same trend is shown where the strain closer to the notch is higher than the boundary strain at the time of failure.

4 Discussion and Conclusion

As a preliminary and feasibility study for a larger spalling characterization test, the process detailed here was successful. Spalling was present as the characteristic mode of failure in both SCNS tests. The numerical models were an accurate prediction of the actual test response. Spalling occurred at the loads predicted and the corresponding

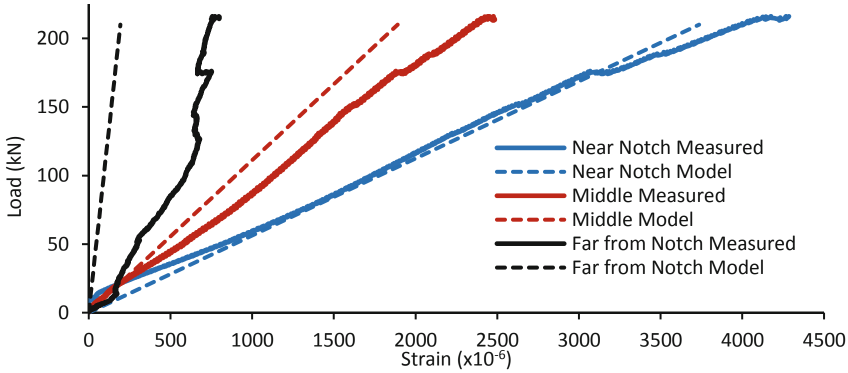

Fig. 5. Predicted and actual strain load

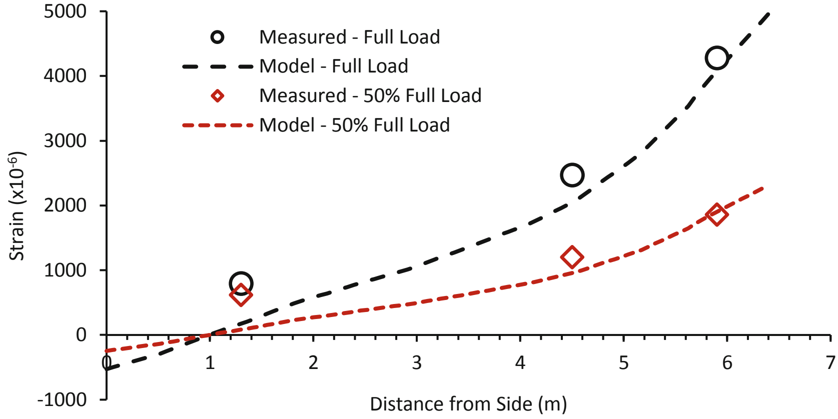

Fig. 6. Predicted and actual strain vs distance along the sample

strains were also like the models. The expected spalling initiation threshold for a borehole of the size used in this experiment suggested by Martin et al. (1994), was similar by being around 1.5 σ_c. A simple loading frame can be used to replicate the experiment without the addition of external forces or constraints. The sample preparation is replicable, and the test can achieve all the gaps that are currently identified in the literature.

While successful to present spalling, the SCNS test still had some issues. Firstly, there was visible crack formation before spalling at different locations. The main implication of this is that the models are less accurate as once a crack develops the stress redistribution is not as predicted making the numerical models less valid. In Fig. 6 this is visualized as the strain near the side is not as expected due to the complicated redistribution. There are other sources of error in this test as well. The Wallace Sandstone was not directly characterized in this study and was assumed to have the literature values. On the data collection side, the effect of the glue on the strain gauge measurement was not accounted for. More can be added to the test to have a better and more robust characterization of spalling. The procedures followed also have room for improvement to increase the overall quality of the test.

The SCNS is a viable and successful method to represent spalling in a laboratory setting. The preparation of the samples and loading conditions of the test can be easily replicated. The numerical models successfully predicted the stress and strain distribution within the sample during testing and gave an adequate prediction of the load required for failure. The load required to break the first sample was 216 kN, which is equivalent to a stress of 30.8 MPa at the top of the sample. The second SCNS sample took a load of 247 kN or 34.1 MPa at the top. The strain measurements using gauges were successful and gave a better understanding of the actual stress redistribution. It also allowed for direct comparison with the numerical models. The test has room for improvement. Better sample preparation, testing procedure, and data collection can be achieved. However, as a feasibility study for a novel spalling test, the SCNS test was a successful one. This test can be further improved on and characterized to increase the understanding of the spalling mechanism.

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