DOI: https://doi.org/10.68732/1b40aab18156e52c

ISBN: 978-9989-2053-6-1

Advances and Challenges in Multiple Failure State Triaxial Testing of Rocks – 50 years' experience

S. Narimani & B.Vásárhelyi
Dept. Engng. Geol. & Geotechn. Faculty of Civil Engng, Budapest Univ. Techn. and Econ., Budapest, Hungary
vasarhelyi.balazs@emk.bme.hu
0000-0002-7779-9506 & 0000-0002-0568-1031

M. Davarpanah
Institut de Recherche en Mines et en Environnement, Rouyn-Noranda, Canada
0000-0002-8046-5814

Abstract

The "Multiple Failure State" (MFS) triaxial test enables several failure points to be obtained from a single specimen through successive loading under increasing confinement, offering substantial time and material savings over conventional tests. Since its introduction by Kovári and Tisa for 50 years ago, numerous modifications - such as the "Continuous Failure State" (CFS) and strain- or volume-controlled variants - have been developed to enhance test reliability. Despite its efficiency, the method's applicability to brittle rocks remains debated due to cumulative damage and strain localization effects. This paper reviews fifty years of research on MFS testing, summarizing theoretical foundations, experimental progress, and comparisons with single-stage triaxial tests. The review identifies key parameters influencing test validity and provides recommendations for improving measurement accuracy and reproducibility in modern rock mechanics laboratories.

Keywords

Failure envelope, Laboratory tests, Multiple Failure Triaxial Test, Continuously Failure Triaxial test.

1 Introduction

Conventional triaxial tests measure intact rock strength under constant confining pressure but require many specimens, making them time-consuming, costly, and impractical for limited core samples. Multi-stage triaxial testing, originating with de Beer (1950) for one test soil specimen, and later the possibility of "Multiple Failure State" (MFS) Triaxial testing for intact rock samples was raised by Kovári and Tisa (1975) 50 years ago, and since then, measurement technology has undergone numerous changes and modifications. This method is faster, cheaper, reduces the effects of sample heterogeneity, and provides more mechanical insight, but despite proven applicability, it is still not universally accepted by rock engineers.Up to now, this laboratory test method has been widely used for several rock engineering projects around the World.Despite numerous measurements demonstrating the method's applicability, this laboratory test is not accepted in all cases. Many rock engineers and researchers reject its use, such as Hoek and Brown (2019).

This review critically evaluates the conceptual foundations, testing methodologies, and practical applications of the Multiple Failure State (MFS) triaxial test, together with its derivative techniques, including the Continuous Failure State (CFS) and modified radial strain-controlled methods. Although MFS testing has been extensively reported as an efficient means of extracting multiple failure points from a single specimen, its validity and reproducibility remain contested due to damage accumulation, strain localization, and inconsistencies in experimental procedures across laboratories. Accordingly, this review aims to clarify the theoretical assumptions and experimental limitations governing the interpretation of MFS results and to propose a unified framework for its appropriate and reliable application in rock mechanics testing.

2 Summary of Multistage Triaxial Testing Methods for Rock Failure Envelope Determination

Over the past decades, several multistage triaxial testing methods have been developed to determine the rock failure envelope using a single intact specimen. Among these, three principal approaches have gained recognition: the Multiple Failure State (MFS) triaxial test introduced by Kovári and Tisa (1975), the Continuous Failure State (CFS) triaxial test proposed by Kovári et al. (1983), and the Modified Multi-Stage Triaxial Test developed by Crawford and Wylie (1987). These methods were designed to reduce material demand while providing reliable estimates of peak and residual strength under varying confining pressures. The MFS and CFS methods have been formally included in the ISRM Suggested Methods as Type II and Type III tests, respectively (ISRM, 2007) – Type I is the "Single State Triaxial" (SST) test.

Regardless of the specific testing procedure, all multistage triaxial tests require the simultaneous measurement of stress–strain relationships and stress–confining pressure curves. Fig. 1 illustrates the chronological evolution of these testing concepts. The early MFS approach introduced the idea of extracting multiple failure points from a single specimen under strain-controlled conditions. This concept evolved into the CFS method, which aimed to approximate the failure envelope through a continuous stress path using servo-controlled confining pressure. Later, the Modified MFS approach simplified stage termination criteria and improved repeatability, especially for brittle and reservoir rocks (Taheri & Chanda, 2013). Recent developments have further advanced these concepts by integrating automated control systems, radial strain gauge feedback, and acoustic or optical monitoring techniques to enhance objectivity and reduce operator influence.

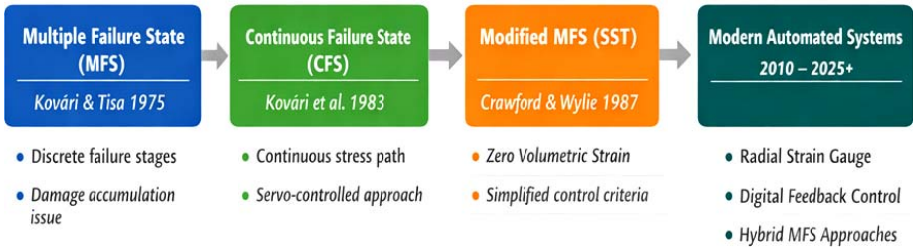


Fig.1 Evolution of multistage triaxial testing methods for rock mechanics.

2.1 Evolution of the Multiple Failure State (MFS) Triaxial Test

The foundation of the MFS concept can be traced back to De Beer (1950), who proposed incremental loading in soil mechanics to generate multiple Mohr circles defining a failure envelope. Building on this idea, Kovári and Tisa conducted systematic rock mechanics experiments at ETH Zürich and formally introduced the "Multiple Failure State" (MFS) triaxial test in 1975. Their method involved applying successive axial loading cycles at increasing confining pressures to a single specimen, as illustrated in Fig. 2.

Kovári and Tisa demonstrated that rock specimens could undergo several distinct strength peaks with negligible variation in peak stress, provided that strain-controlled loading was applied. Experimental results from Buchberg sandstone and Carrara marble showed consistent peak strengths across multiple loading stages, confirming the feasibility of the method for certain rock types. Importantly, the MFS technique was also shown to be suitable for determining residual failure states. The theoretical background of the method was explained using the Prandtl–Reuss hypothesis, which provided a constitutive framework for interpreting the observed stress–strain behaviour.

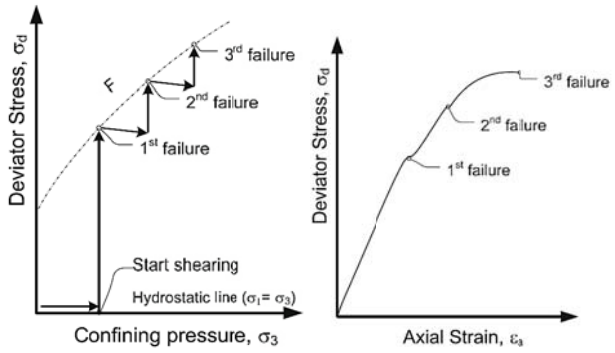


Fig. 2 Multi-stage triaxial test a) stress paths b) stress-strain relation (Youn and Tonon, 2010).

2.2 Continuous Failure State (CFS) Triaxial Test

In the early 1980s, Kovári et al. (1983) proposed the Continuous Failure State triaxial test as a refinement of the MFS concept. In this method, the specimen is initially loaded axially under a fixed confining pressure until signs of failure appear. At this point, the slope of the stress–strain curve, corresponding to Young's modulus, is determined (Fig.3). Subsequently, axial stress continues to increase at a constant strain rate while the confining pressure is simultaneously adjusted to maintain this slope.

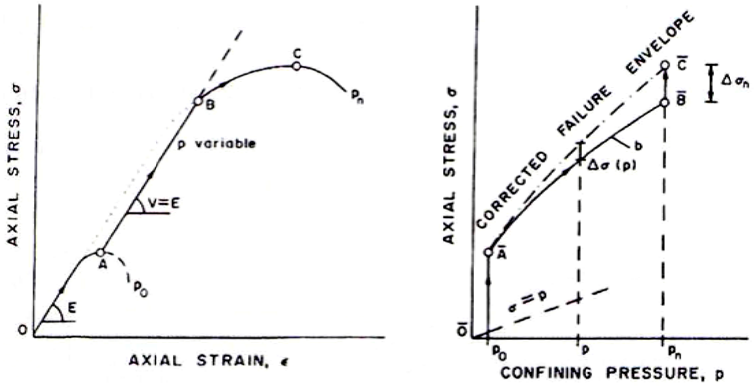


Fig. 3 Concept of the continuous failure state (CFS) triaxial test proposed by Kovári et al (1983). The high slope ratio V/E = 1.0 leading into pre-failure state with reserve of strength $\Delta\sigma n$.

The objective of the CFS method is to preserve a continuous pre-failure state by keeping the stress path tangential to the yield surface until final failure occurs. As a result, the test generates a sequence of closely spaced failure states rather than discrete peak points. The method is based on three key assumptions: the uniqueness of peak strength functions, the reproducibility of stress–strain curves near peak stress, and the independence of material state from the specific stress path followed. According to Kovári's theoretical investigations, these assumptions closely approximate real rock behaviour.

The main innovation of the CFS test lies in its ability to trace a smooth stress trajectory that approximates the true failure envelope more accurately than discrete multistage methods. By minimizing unloading–reloading cycles, the method reduces cumulative damage between stages, which had been a major limitation of the original MFS technique. However, practical implementation of the CFS test is demanding, as it requires highly responsive servo-control systems to maintain the ideal stress ratio. Minor control delays may lead to premature yielding or increased data scatter.

Subsequent studies confirmed the feasibility of the CFS approach using automated feedback control systems, and later research demonstrated its potential for estimating residual failure envelopes in brittle rocks. Nevertheless, the applicability of the method strongly depends on material properties. While it performs well for moderately ductile and homogeneous rocks, its reliability may decrease for highly brittle or heterogeneous specimens due to strain localization and irreversible damage.

2.3 Modified Multi-Stage Triaxial Test

To simplify multistage testing while maintaining reliable failure envelope estimation, Crawford and Wylie (1987) introduced the Modified Multi-Stage Triaxial Test. This approach uses zero volumetric strain as an objective criterion for terminating each loading stage. The procedure, illustrated in Fig.4, involves hydrostatic loading to the desired confining pressure, resetting strain readings, axial loading

until volumetric strain returns to zero, and unloading back to the initial hydrostatic stress. This sequence is repeated at progressively higher confining pressures.

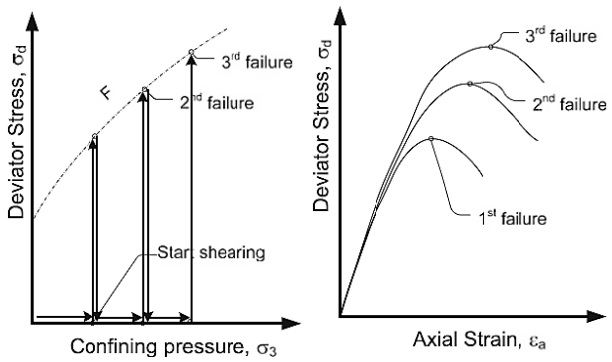


Fig. 4 Modified multi-stage triaxial test a) stress paths b) stress-strain relation (Youn and Tonon, 2010).

Experimental studies on Berea sandstone and Bonnet granite showed that the zero volumetric strain criterion provided reasonable predictions of the failure envelope when compared with conventional triaxial tests. However, for very brittle materials, premature failure sometimes occurred before completion of the planned multistage sequence. To address this issue, the method was later modified by using a volume change ratio relative to a maximum volume change, although this parameter was not clearly defined.

Overall, the Modified MFS approach demonstrated that simplified and objective control criteria could yield reliable failure envelope estimates, particularly for reservoir and moderately brittle rocks. These developments laid the groundwork for modern automated multistage triaxial testing systems, which combine digital control, real-time sensing, and advanced monitoring techniques to improve accuracy, repeatability, and applicability across a wide range of lithologies.

3 Summary of Multi-Stage Triaxial Test

To clarify how the Multiple Failure State (MFS) and Continuous Failure State (CFS) testing concepts have evolved and been applied across different rock types and laboratory conditions, a chronological summary of the principal comparative and methodological studies is presented in Table 1. This structured overview highlights the progressive refinement of the technique, from its conceptual origin in the 1970s to recent implementations using automated radial-strain and volumetric-control systems, and identifies both consistent findings and remaining uncertainties in how MFS/CFS results relate to standard strength parameters.

4 Practical limitations and applicability of MFS/CFS methods

Although MFS and CFS triaxial tests can derive strength parameters from a single specimen, their applicability is limited by damage accumulation, rock type, instrumentation, and data interpretation. Accumulated microcracking can reduce apparent strength in later stages, especially in brittle rocks, while more ductile lithologies remain less affected. Test reliability decreases with increasing brittleness and heterogeneity and depends strongly on precise servo-control and objective failure criteria. Subjective stage-termination and cumulative damage complicate parameter fitting, making non-linear strength models preferable. Overall, MFS/CFS tests are effective when samples are limited and materials are moderately ductile and homogeneous, but single-stage or hybrid approaches are better suited for highly brittle or heterogeneous rocks.

5 Future Perspectives: Automation, Digital Sensing, and Data-Driven MFS Testing

Over the past 50 years, the MFS triaxial test has progressed toward semi-automated systems, with the next major shift driven by automation, advanced sensing, and data-driven analysis. Automated control and objective stage-termination criteria significantly reduce variability and improve reproducibility, while AI-assisted controllers enable adaptive, quasi-static loading. Integrated sensing techniques - such as DIC, acoustic emission, fiber-optic strain sensing, and X-ray CT—allow early detection of damage, reduce subjectivity, and support the development of digital twins. High-density data from automated tests enable machine-learning models to reliably estimate mechanical parameters and classify material behaviour, improving efficiency and standardization compared to conventional

interpretation methods. Unsupervised ML clustering also helps identify brittle–ductile transitions or classify lithologies based on AE signatures and strain energy release patterns (Koosmen et al., 2023). These approaches allow rapid, standardized interpretation of large experimental databases, reducing dependence on manual curve-fitting of Mohr–Coulomb or Hoek–Brown envelopes (Hoek and Brown, 2019; Vásárhelyi et al., 2016). Table 2 summarizes improvement of reliability and efficiency of MFS testing from the point of automation, sensing, and data-driven approaches.

Table 1. Selected major studies on MFS/CFS and short comparison notes.

Reference	MFS/CFS variant/method notes	Main difference vs SST (qualitative)/reported bias
Kovári and Tisa, (1975)	Original Multiple Failure State and Strain-Controlled concepts; theoretical and early lab demonstration	Introduces concept: derive multiple failure points from one specimen; emphasizes instrumentation and stopping rules.
Kovári, et al. (1983)	Continuous failure state / steady stress-path control; theoretical/procedural paper	CFS maintains specimen at failure while changing stress path to trace envelope.
Crawford and Wylie (1987)	Modified MFS variants for reservoir cores — staged confining increases	Used successfully for reservoir cores where sample availability limited; stresses that corrections and careful control required.
Pagoulatos (2004)	MFS variants; volumetric inflection / ΔV/V stopping criteria	Generally close agreement for Berea sandstone with careful stopping rules; differences depend on stopping criterion (authors analyze sensitivity).
Youn&Tonon, (2010)	"Multi-stage triaxial test on brittle rock"; focus on brittle response and post-peak staging	Finds multi-stage can reproduce envelope but brittle instability and localization increase scatter and possible underestimation of peak strength if unloading chosen poorly.
Alsalman, (2015)	Comparison & proposed correction methods to map MST→SST results	Proposes corrections for systematic biases arising from damage accumulation; reports numeric adjustments/improvements.
Kotsanis et al., (2018)	Statistical processing of multistage tests; many stages per specimen	Demonstrates practical efficiency for scarce core material; discusses increased scatter for brittle lithologies.
McKean et al., (2019)	MFS applied to unconventional reservoir cores; demonstrated pre/post-peak characterization	MFS captured pre/post peak behavior for heterogeneous cores; recommended instrumentation improvements.

Table 2. Summary of automation, sensing, and data-driven approaches improving reliability and efficiency of MFS testing.

Technology/ Approach	Function in MFS Testing	Key Advantages	Representative Studies (2020–2025)
Automated closed-loop control	Real-time servo-hydraulic control of σ_1–σ_3; auto stage termination	Removes operator bias; improves reproducibility	Csuhanics & Debreczeni (2013); Jin et al. (2025)
Radial-strain-gradient (RSG) criterion	Objective stage termination	Rock-type independent; high repeatability	Jin et al. (2025)
Digital Image Correlation (DIC)	Surface strain mapping	Captures localization, non-contact	McKean et al. (2019); Youn & Tonon (2010)
Acoustic Emission (AE)	Microcrack activity detection	Detects onset of damage	Choi et al. (2018); Koosmen et al. (2023)
Fiber-optic sensing (FOS)	Distributed strain sensing	High spatial resolution	Gholizadeh et al, (2024)
Machine-learning analysis	Parameter inference from MFS data	Reduces human bias, handles nonlinearity	Trinh et al. (2025)
Digital twin coupling	Real-time model–test feedback	Predictive control, adaptive loading	Minaeian et al. (2020)

6 Conclusion

Over the past five decades, Multiple Failure State (MFS) and Continuous Failure State (CFS) triaxial testing have evolved into established laboratory techniques in rock mechanics. This review demonstrates that the reliability of MFS/CFS methods is strongly dependent on rock type. For ductile to moderately brittle rocks, including shales, weak sandstones, and porous sedimentary formations, multistage tests reproduce single-stage strength envelopes with reasonable accuracy. In contrast, for highly brittle, low-porosity crystalline rocks, conventional MFS methods may underestimate peak strength. Consequently, single-stage triaxial testing remains the reference approach for peak strength determination when sufficient core material is available, whereas MFS/CFS testing offers a reliable and cost-effective alternative when sample availability is limited or residual behaviour is of primary interest.

Acknowledgement

The financial support of the Hungarian-Croatian bilateral project National Research, Development and Innovation Fund, grant no: 2023−1.2.4.-TéT-2023-00044 is acknowledged.

References

Alsalman M (2015) *Comparison and correction of multistage triaxial tests to single stage triaxial test for the rock mechanical testing.* MSC Thesis, Univ. Houston, p. 97.

Choi JH, Dai S, Lin JS, Seol Y (2018) Multistage Triaxial Tests on Laboratory-Formed Methane Hydrate-Bearing Sediments.*J. Geoph. Res.: Solid Earth,* 123(5), 3347–3357. Doi: 10.1029/2018JB015525

Crawford AM, Wylie DA (1987) *A modified multiple failure state triaxial testing method.* In: Proc. 28th US Symp. Rock Mechanics, Tucson; 133–140.

Csuhanics B; Debreczeni Á (2013) Development of automatic control of multi-stage triaxial tests at the University of Miskolc. *Geosciences and Engineering*, 2(3): 37-43.

De Beer IEE (1950) The cell-test. *Géotechnique*, 2(2): 162–172.

Gholizadeh Doonechaly N, Reinicke A, Hertrich M, Plenkers K, Obermann A, Fischli F, Maurer H; Wiemer S (2024) Multiphysics monitoring of cementation operation: Implications for wellbore integrity and hydrogeological characterization. *Env. Earth Sci.,* 83(5), 146.

Hoek E, Brown ET (2019): The Hoek-Brown Failure criterion and GSI – 2018 edition. *J Rock MechGeotechnEngng*11:445-463.

ISRM (2007) *The complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006*. Eds: R. Ulusay and J. Hudson, ISRM Turkish Nat. Group & ISRM.

Jin G, Syed SA, González-Pérez HJ, Kwak HT, Yousef AA, al Dhamen AA (2025) New unloading criterion for enhancing multi-stage triaxial tests based on radial strain gradient. *J. Rock Mech. Geotechn. Engng,* 17(8), 4735–4744.

Koosmen K; Serati M; Craig B (2023) *Multistage triaxial testing of intact rock: volumetric strain-based methods applied to rock slope design*. In PM Dight (ed.), SSIM 2023: 3. Int. Slope Stability in Mining Conf. Australian Centre for Geomechanics, Perth, 343-358

Kotsanis D; Nomikos PP; Rozos D; Soffianos AI (2018) Multistage triaxial testing of various rock types: A case study of East Attica Prefecture, Greece. *Procedia Structural Integrity*, 10: 112-119.

Kovári K; Tisa A (1975) Multiple failure state and strain controlled triaxial tests. *Rock Mech* 7:17-33.

Kovári K; Tisa A; Attinger RO (1983)The Concept of "Continuous Failure State" Triaxial Tests. *Rock Mech. Rock Engng*. 16: 117–131.

McKean SH; Priest JA (2019) Multiple failure state triaxial testing of the Montney Formation, *J. Petr. Sci. Engng*, 173, 122-135.

Minaeian V, Dewhurst DN, Rasouli V (2020) Aninvestigation on failure behaviour of a porous sandstone using single-stage and multi-stage true triaxial stress tests. *Rock Mech. Rock Engng,* 53(8), 3543–3562.

Pagoulatos A (2004) *Evaluation of multistage triaxial testing on Berea Sandstone.*MS thesis, Univ. of Oklahoma; p. 130

Taheri A; Chanda E (2013) *New multiple-step loading triaxial test method for brittle rocks*, Proc. 19.NZGS Geotechnical Symp. Ed. CY Chin, Queenstown

Trinh NQ; Grøv E; Vistnes G (2025) A Comparative Study of UCS Results Obtained from Triaxial Tests Under Multiple Failure State Conditions (Test Type II). *ApplSci (Switzerland),* 15(6), 3176.

Vásárhelyi B, Kovács L, Török A (2016) Analysing the modified Hoek–Brown failure criteria using Hungarian granitic rocks. *GeomechGeophys Geo-energ Geo-resour* 2:131–136.

Youn H; Tonon F (2010) Multi-stage triaxial test on brittle rock. *Int. J. Rock Mech. Min. Sci*. 47: 678-984.