INVESTIGATION OF MECHANICAL PROPERTIES
OF IN-SERVICE MATERIALS USING SMALL PUNCH TEST

A

SYNOPSIS

submitted by
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# Table of Contents

1 Introduction........................................................................................................................................2
2 State of the art of research topic........................................................................................................4
3 Problem definition ...................................................................................................................................6
4 Objective and Scope of work ................................................................................................................7
   4.1 Objective ........................................................................................................................................7
   4.2 Scope of work..................................................................................................................................7
5 Original contribution by the thesis.........................................................................................................8
6 Research Methodology ........................................................................................................................9
   6.1 Research approach breakdown .....................................................................................................9
   6.2 Testing approach ............................................................................................................................9
      6.2.1 Experimental physical testing ...............................................................................................9
      6.2.2 Numerical FE simulation testing ..........................................................................................10
   6.3 Yield & Ultimate strengths estimation approaches ........................................................................12
      6.3.1 Yield tensile strength ............................................................................................................12
      6.3.2 Ultimate tensile strength ....................................................................................................14
   6.4 Numerical Finite Element (FE) simulation driven SPT study ....................................................15
      6.4.1 FE methodology calibration ..................................................................................................16
      6.4.2 Material data set ................................................................................................................16
7 Achievements with respect to objectives ..............................................................................................19
   7.1 Yield strength correlation ............................................................................................................20
   7.2 Ultimate strength correlation ......................................................................................................22
8 Conclusion .............................................................................................................................................24
9 List of publications .............................................................................................................................25
10 References ..........................................................................................................................................25
# Introduction

The periodic estimation of remaining fitness for service of in-service system is crucial to assess for many of the critical applications where human and environmental safety is involved, like nuclear reactor, boiler feed pump etc. The traditional mechanical tests need large sets of material volumes to be extracted from in-service system without compromising its reliability to determine the various strength parameters to estimate the preserved reliability. This prerequisite makes traditional testing approach an unviable to meet the objective for most of the industrial system applications. Therefore, the industries which involve irradiated and embrittled substances [1],[2],[3],[4] are predominately relying on small punch test (SPT).

The small punch test (SPT) is a non-destructive testing method used to estimate the mechanical properties of materials, such as yield strength, ultimate tensile strength, and ductility in situ state of specimen. This test involves a tiny/miniature specimen size of $\phi 8\text{mm} \times 0.5\text{mm}$ [5] thick circular plate so that such a smaller volume extraction been easy using special purpose devices. This helps to grow prominence of this technique to be expanded for many of the general engineering systems too. This SPT technique first ever evolved during late 1980 by many researchers [6],[7],[8],[2].

As shown in Fig. 1, the SP test apparatus includes a miniature specimen, the lower and upper dies, spherical tipped punch, or spherical ball punch separately. the specimen is firmly clamped in-between the dies whereas the specimen is indented using the spherical punch at a gradual load, causing the specimen to deform plastically until it ruptures. The load-displacement curve obtained during the test is used to estimate the mechanical properties of the material. Although the SPT is quick and non-destruction to estimate the mechanical properties, the reliability and accuracy of the SPT results are significantly influenced by adopted test procedure, approach adopted for load-displacement response measurement, and its subsequent results interpretation followed by traditional uniaxial strengths estimation using proclaimed correlations. Therefore, it is critical to standardize the testing approach and appropriate calibration procedures to ensure the accurate and consistent SPT results.

In attempt to define a universally accepted approach for SPT-aided mechanical characterization, many standards were published including (i) CWA 15627:2007 [9] by European Committee For Standardization (CEN), (ii) ISO/TR 29381:2008(E) [10] by the International Organization for Standardization (ISO), and (iii) British standard BS EN
10371:2021 [5]. However, it was recognized that such standards were not concerned to practice a consistent approach while SPT response measurement, its appropriate post-processing while estimating strengths.

![Schematic representation of the SPT apparatus](image)

**Fig. 1** Schematic representation of the SPT apparatus [9]

Where, (1) = miniature specimen, (2) = hemispherical tipped rigid punch, (3) = lower die, (4) = upper die, (5) = LVDT to measure specimen deflection, \( u/v \) = deflection/displacement, \( F \) = applied load, and \( h_0 \) = initial specimen thickness, \( d_1, d_2, r \) = relevant component sizes.

The objective of this research study is to make systematic review of SPT best practices and check viability of proclaimed best-fit empirical correlations for uniaxial strengths estimation followed by establishing comprehensive correlations for accurate strengths estimation for the metallic materials which are exposed to 100-2000 MPa strengths, which naturally covers the widest spectrum of industrial material applications. For this research, systematically 206 material datasets were designed as listed in Table 3, by varying key influential parameters filtered with reference of sensitivity study made. Such material datasets cover extreme ranges of elastic-plastic mechanical properties including strength range of 100-2000 MPa of metallic materials. It was a cumbersome task do small punch testing for such a large set of materials through physical small punch experimental test. Hence, the numerical FE simulation-driven approach was leveraged as a its substitute.
Although in recent years, there have been significant advancements are made in the Finite element modelling (FEM) aided numerical modelling techniques of the SPT process to deliver the accurate and consistent test results, it’s essential to calibrate and benchmark FEA simulation methodology to match its competence at par to physical small punch experimental test. For such calibration exercises, the physical small punch test was performed over casted ductile iron, EN 1563 GJS 400, and cast stainless steel, EN 10213-4 Gr. 1.4408 proprietary materials. This physical small punch test was performed at India’s one of the most reputed research institute “Indira Gandhi Centre for Atomic Research, Kalpakkam (IGCAR), INDIA [11]”. Apart from proprietary materials, the experimental results from reputed literatures [12],[13],[14],[15] were referred as listed in Table 2. As shown in Fig. 6, the FE-simulated SPT responses were compared with Table 2 outlined experimental test responses where comparative results fits well over elastic-plastic regime of load-displacement curve which conforms the accuracy of calibrated FE simulation SPT model and methodology. Such calibrated FE modelling practice was continued to follow for due course of the research to test Table 3 listed 206 designed materials.

Subsequently, the numerically evaluated load-displacement/load-deflection SPT response data were systematically analysed by means of Wolfram Mathematica [16], a prominent mathematical modelling tool to formulate the improved & comprehensive best-fit correlations to be fit for any SPT response post-processing approach. The data fittings are demonstrated and discussed in section 7. Later, the improved and comprehensive correlations were validated.

### 2 State of the art of research topic

The small punch test was first developed at MIT for radiation embrittlement studies and reported by Manahan et al. [6] and further research was extended by Mao et al. [17] to acknowledge the small punch test apparatus and outlined the linear correlations to estimate mechanical strength with reference of interpreted mechanical forces from load-displacement response.

Later, an attempt made at Japanese Atomic Energy Research Institute (JAERI) by Takahashi et al. [18] to standardize the SP test practice for metallic materials to determine the ductile to brittle transition temperature (DBTT) and elastic-plastic fracture toughness ($J_C$). The first-ever attempt was made in Europe by European Committee For Standardization (CEN) through the

Traditionally the flat circular or square-shaped, 0.2-0.5 mm thick miniature specimens were explored by X. Mao et al. [17]. However, Simonovski et al. [15] had conducted an SP test over the flat and curved specimens to verify the specimen’s geometrical stiffness sensitivity for mechanical characterization.

The extracted specimen displacement against indented load, load-displacement curve had been classified into four zones by Kameda et al [19]. I- Elastic bending of the specimen due to contact with indenter, II- Plastic bending due to continuous deflection, III- Plastic membrane stretching happens after reaching certain plastic bending limit and IV- Plastic instability where necking and specimen cracking starts after reaching maximum load whereas fracture is happening in different regime with reference of its fracture toughness. Fleury et al. [20] verified the validity of all the four zones by performing an SP test using austenitic 12Cr-1Mo and 1Cr-0.5Mo steels specimens along with temperature variation. Lucas et al. [21] experimentally investigated the effects of indenter ball size and specimen thickness on the SPT L-D response.

The X. Mao et al. [17] proposed the two-tangent method to define yield force to evaluate at the intersection of two tangent lines are drawn from the elastic and plastic bending curves, which later corrected by CEN CWA 15627:2007 [9], to define the yield force vertical line intersection of two tangent lines and load-displacement curve. Garcia et al. [12] performed SPT on 16 different material grades of structural steel to stainless steel metal alloys, to scrutinize the best-fit approach for the yield and ultimate strengths estimation. Author proposed the distinct empirical correlation factors, which were later optimised by Bruchhausen et al. [22].

Janca et al. [23] attempted to improve the linear correlations superior than CWA method. They correlated yield strength as a function of yield force Py1.5, which was denoted over load-displacement (L-D) curve, where the area under the curve is 1.5 times greater than the
complimentary area above the curve. Jose Calaf-Chica et al. [24] claimed that yield strength estimation doesn’t only rely on elastic-plastic transition load obtained with the t/10 offset method but also on the minimum slope \( \text{slope}_{\text{min}} \) during the membrane stretching region (strain hardening region) of the L-D curve. Eventually, some of the researchers have also attempted to establish the non-linear correlation Like, Eskner et al. [25], Fleury et al. [20] analyzed the elastic deformation using classical plate bend theory, and found a good agreement between SPT biaxial results with uniaxial tensile data. Jose Calaf-Chica et al. [26] studied the deviation in yield and ultimate strength estimation in absence of material isotropy and the Bauschinger effect. He observed that in absence of isotropy, the coefficient of yield strength correlation becomes invalidated. Isselin et al. [27] have proposed a unique elastic energy compliant approach by correlating it with force to yield strength. The authors stretched the specimen until maximum force to gain extreme plasticity and subsequently unloaded it at the same rate. The area under the L-D curve measured which was observed while reverse deflection until elasticity and defined the elastic energy \( E_{\text{el}} \) as a function of stress.

The initial slope \( \text{slope}_{\text{ini}} \) of L-D curve plotted using \( t_0/10 \) offset method to define Young’s modulus of elasticity \( (E) \) as proposed by Cuesta et al. [28]. Vorlicek et al. [29] attempted to characterize the mechanical properties for the low-alloy ferritic steel and demonstrated the analytical formulation for \( (E) \), as a function of various SPT geometrical parameters. Jose Calaf Chica et al. [30] studied the sensitivity of \( \text{slope}_{\text{ini}} \) for unloading/loading (UL) cycles and proposed the slope determination with reference of unloading cycle because it exhibits the pure elastic behaviour and independent of Poisson’s ratio influence.

Many of the researchers [22][20][12][31] accomplished their SPT research outcome by exploring the numerical simulation FEA techniques complimented by the ABAQUS numerical analysis tool whereas the FEA simulation in this research study has been conducted by ANSYS Mechanical Enterprise 2020 R2 FE [32] tool.

3 Problem definition

As mentioned earlier, there are three [9],[10],[5], prominent standards published in small punch testing domain. However, upon the comparison of them, it is noted that their proposed recommendations neither emphasized for consistent practicing of force-specimen deflection, \( (F - u) \) / force-punch displacement, \( (F - v) \) SPT responses nor mechanical forces and
strength estimation approach. Through the detailed investigation performed for this study, it is recognized that estimated strengths significantly scatter by practicing even latest EN 10371:2021 [5] standard proposed recommendations while covering the materials of 100-2000 MPa of exposed strengths.

Moreover, whatever the proclaimed best-fit correlations are published so far by many of the researchers are distinctly works well for particular class of materials strength estimation only. This limitation is also one of the drawbacks to make SPT a versatile technique.

Therefore, it is critical to establish an unambiguous procedure to secure accurate and consistent mechanical characterization which is even applicable for universal class of metallic materials.

4 Objective and Scope of work

4.1 Objective

The main objectives of this research study are:

- Detailed investigative review of so far established best practices to estimate the mechanical properties of in-service materials using small punch test technique.

- Validation of various load-displacement SPT response post-processing approaches in practice and pro-claimed correlations.

- Accuracy assessment while using best practices proposed by numerous published standards for strength estimation for the universal class of metallic materials.

- Establish consistent best practice and comprehensive correlations to estimate the conventional uniaxial mechanical strengths for the wider class of metallic materials.

4.2 Scope of work

The scope of work had been confined for following activities:

- Comprehensive literature review to understand the recent developments are made in SPT domain and unveil potential research gap.
➢ Assessment of various SPT approaches and correlation for mechanical characterisation for wider class of materials.

➢ Sensitivity study to understand potential impact of various SPT parameters.

➢ Calibration of FE simulation driven numerical methods with experimental small punch test.

➢ Designing of large sets of material data which covers wider class of materials to undergo small punch testing.

➢ Conduct small punch testing through FE simulations over designed materials and measurement of load-specimen deflection as well as load-punch displacement curves.

➢ Validation of estimated mechanical forces and strengths using various SPT approaches and correlations.

➢ Optimise and establish comprehensive correlations for accurate estimation of conventional uniaxial mechanical strengths for the wider class of metallic materials.

5 Original contribution by the thesis

There are numerous advancements made through this research study which holistically evolves mechanical strengths estimation of in-service system by means of small punch testing technique. Such advancement follows as :

➢ Brought greater insight for mechanical characterisation by small punch testing while performing detailed sensitivity study.

➢ Unveil the potential impact on mechanical strength estimation due to inconsistency SPT response postprocessing approaches and best-fit correlations proclaimed by many researchers and standards.

➢ Established comprehensive correlations which accurately estimates conventional uniaxial mechanical strengths for the wider class of metallic materials which are exposed to 100-2000 MPa strengths.
The mechanical strengths estimation enhanced for accuracy $R^2 > 0.95$, and error confinement to ±10%, irrespective of SPT practice and class of material to test. Earlier such accuracy varied for $R^2 = 0.72-0.87$ for particular class of materials even using the best practices recommended by recently published EN 10371:2021 [5] standard.

6 Research Methodology

6.1 Research approach breakdown

The approach for this research study was inspired by DMADV, a systematic approach to solve the problem where various phases of work had been classified into 5 different phases as per Fig. 2.

**Fig. 2** Research work-break down in DMADV approach

6.2 Testing approach

6.2.1 Experimental physical testing

The SPT is often conducted on a miniature specimen which is post-processed from the material extracted from the in-service component. P. Patel et al. [33], described the series of activities
as a process to prepare miniature specimens to be shaped into a standard size. This process initiates with scooping aged material using mechanically powered sampler machines [34]. Later, such materials are formed into miniature blanks [9] through EDM cutting, followed by polishing to make them compatible for SPT.

As shown in Fig. 1, the SPT fixture consists of lower-upper dies and rigid hemispherical tipped indenter/punch which was mounted on the universal test machine (UTM). A miniature specimen was firmly clamped between the dies, and the specimen was gradually indented utilizing a hemispherical punch. An experimental SP tests were conducted over the proprietary casted ductile iron, EN 1563 GJS 400, and cast stainless steel, EN 10213-4 Gr. 1.4408 materials, by small punch testing machine exists at “Indira Gandhi Centre for Atomic Research, Kalpakkam (IGCAR), INDIA [11]”. This test machine was screw driven UTM of 10kN capacity. The equipment had a measuring resolution of 1N for force, and 1μm for displacement. The standard size [5] specimen was indented at a rate of 0.5 mm/min using 10kN of the load cell until it ruptured. The specimen deflection, \( u \) recorded while indention, and those force-deflection \((F - u)\) responses are plotted.

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Specimen Diameter ( (d_1) ) [mm]</th>
<th>Specimen Thickness ( (h_0) ) [mm]</th>
<th>Lower Die Diameter ( (d_2) ) [mm]</th>
<th>Punch Radius ( (r) ) [mm]</th>
<th>Chamfer Length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard</strong></td>
<td>( \phi 8 \pm 0.1 )</td>
<td>( 0.5 \pm 0.005, Ra &lt; 0.25 \mu m )</td>
<td>( \phi 4 )</td>
<td>1.25</td>
<td>0.2</td>
</tr>
</tbody>
</table>

### 6.2.2 Numerical FE simulation testing

Most of the SPT domain studies that have been conducted in recent decades, were supplemented through FE simulation-driven numerical approach, along with traditional experimental testing in order to bring greater insight. The FE simulation software is competent at simulating real-world physical experimental boundary conditions and capturing the structural behaviour of specimens. This research study is supported by experimental testing and ANSYS [32] software-powered FE simulation to make it feasible to test a large set of material data.
A 3D axisymmetric SPT fixture including specimen geometry, was modelled by a 2D axisymmetric idealization feature, which is shown in Fig. 3. Such idealization helps to enhance FE solution accuracy at accelerated computation time. The PLANE182, a 4-node quadrilateral 2D element was used to mesh the geometry. The specimen squeezed between upper and lower dies with bonded connection across the projected contact surfaces, while all other contact interactions had 0.2 friction coefficient. A load indentation is created by displacing the hemispherical punch by 2mm.

The Gurson, Tveergard, and Needleman (GTN) constitutive damage [35],[36],[37] material model is considered for a specimen to capture its inherent elastic-plastic-damage behaviour, whereas all other geometries are assumed as a rigid body. GTN model assumes spherical voids in an elastic-plastic continuum which replicates the reduced load-carrying capacity of material before failure. The void volume fraction, $f$, is used as a measure of damage. The nucleation porosity, $f_n$ signifies the volume fraction at which void nucleation takes place in the material which replicates in the slight softening effect that occurs in practical metals. In this study $f_n$, is set to 0.01, due to its best fitting to predict damage behaviour. Material’s plasticity is characterised by multilinear isotropic hardening (MISO) model derived from Ramberg-Osgood material plasticity model, apart from GTN damage model to represent the plasticity evolution with reference of metal porosity.

![Fig. 3 FE simulation boundary conditions](image-url)
6.3 Yield & Ultimate strengths estimation approaches

6.3.1 Yield tensile strength

The yield and ultimate strengths of any material coupled with the strains, which is used to establish the mechanical elastic-plastic stress-strain constitutive relationship. The uniaxial yield strength for metals is often determined at an offset of 0.2% plastic strain [38], which in turn seems at the plateau of the elastic-plastic transition.

According to proposal made by several studies [12],[39],[27],[9],[5],[40], the yield strength, $\sigma_y$, correlates as a linear function of elastic-plastic transition force, $F_e$, per Eq. (1). Therefore $F_e$ must be predetermined to evaluate the yield strength.

$$\sigma_y = \beta_y \frac{F_e}{h_0} \quad \ldots (1)$$

Where, $\beta_y$ is material-dependent empirical constant, $F_e$ = yield force, and $h_0$ = initial specimen thickness.

As per a procedure agreed by the European committee for standardization (CEN) wide CWA 15627:2007 [9], yield strength can be correlated through elastic-plastic transition force, $F_e$ as a bilinear function of punch displacement, $f(v)$. Later, such procedure improved in recently released CEN approved European standard EN 10371:2021 [5], where they proposed $F_e = f_A$, and it corresponds to either bilinear function of specimen deflection, $f(u)$, or alternatively trilinear function of punch displacement, $f(v)$. Contrast to CEN standards, ASTM E3205-20 [40] proposed $F_e \neq f_A$, and it correlated as a bilinear function of specimen deflection, $f(u)$. The derivation of $F_e$ using bilinear function follows the Eq. (2), supported by the least square fit method, as a function of $f(u)$. Whereas derivation of $F_e$ as function of $f(v)$, supported through trilinear function per Eq. (3). The depiction of data points A, B, $F_e$, and $f_A$ using various methods are illustrated through Fig. 4 (A), (B), (C) and (D) accordance to various standards [9],[5],[40]. In this paper, wherever the elastic-plastic transition force corresponds to $F_e \neq f_A$ and $F_e = f_A$, has been denoted as $F_{ee}$ and $F_{eA}$ respectively.
Bilinear Method [5]:

\[
f(u) = \begin{cases} 
\frac{f_A}{u} u \\ \frac{f_B-f_A}{u_B-u_A} (u - u_A) + f_A 
\end{cases} \quad \text{for } 0 \leq u \leq u_A, \\
\text{for } u_A \leq u \leq u_B, \\
\text{err} = \int_u^u [F(u) - f(u)]^2 \, du
\]

Trilinear Method [5]:

\[
f(u) = \begin{cases} 
0 \\ \frac{f_A}{v_A - v_0} (v - v_0) \\ \frac{f_B-f_A}{v_B-v_A} (v - v_A) + f_A 
\end{cases} \quad \text{for } 0 \leq v < v_0, \\
\text{for } v_0 \leq v < v_A, \\
\text{for } v_A \leq v \leq v_B, \\
\text{err} = \int_v^v [F(v) - f(v)]^2 \, dv
\]

Fig. 4 Estimation of yield force, \(F_e\) according to: (A) \(f(v)\), CWA 15627:2007 [9]; (B) \(f(u)\), EN 10371:2021 [5]; (C) \(f(v)\), EN 10371:2021 [5]; (D) \(f(u)\), ASTM E3205-20 [40]
6.3.2 Ultimate tensile strength

The ultimate tensile strength, $\sigma_u$, is also correlated as a function of maximum load, $F_m$ using Eq. (4), according to the literature [12],[13].

$$\sigma_u = \beta_{um} \frac{F_m}{h_0 u_m} \quad \ldots (4)$$

Where, $\beta_{um} = 0.2784$ for $R^2 = 0.7472$ [5], is a material-dependent empirical constant, $F_m = \text{maximum force}$, $h_0 = \text{initial specimen thickness}$, and $u_m = \text{maximum deflection}$

Whereas, E. Altstadt et al. [41] proposed $F_i$ driven linear correlation using Eq. (5), where $F_i$ is the intersecting force at the onset of plastic instability and corresponding to specimen deflection $u_i = 1.1h_0$ and punch displacement $v_i = 1.29h_0$.

$$\sigma_u = \beta_{ui} \frac{F_i}{h_0} \quad \ldots (5)$$

Where, $\beta_{ui} = 0.1828$ for $R^2 = 0.87$ [5], is SPT experimentally derived parameter, $F_i$ = intersecting force, and $h_0$ = initial specimen thickness.

The recognition of ultimate force, $F_m$ is simple because in ductile materials once stress-strain reaches its permissible limit, stress suddenly starts to fall upon continued loading due to neck formation initiation. As reflected in Fig. 5, such characteristic is also clearly evident in SPT $F - u$, and $F - v$, responses, where ultimate force, $F_m$ can be denoted at the peak force apart from intersecting force, $F_i$. With reference of derived $F_m$ and $F_i$, the ultimate strength, $\sigma_u$ can be estimated using Eq. (4) & Eq. (5), the two distinct correlations, but their accuracies are sensitive to the material-dependent constants, $\beta_{um}$ & $\beta_{ui}$.

As studied by P. Patel et al. [33], researchers have worked extensively and proclaimed their outlined constant values as the best fit in an attempt to develop material-independent constants $\beta_y$, $\beta_{um}$, $\beta_{ui}$, corresponds to the yield, and ultimate strength estimation. Recently EN 10371:2021 [5] has also calibrated and proposed $\beta_y = 0.510$, $\beta_{um} = 0.2784$, and $\beta_{ui} = 0.1828$ as a best fit constants for the strengths estimation for the steels having yield strength between 200-1000 MPa. However, the considerable variation are noticed among the proclaimed best-fit values through various assertions [5],[33]. Moreover, Fig. 5 denoted $F - u$ and $F - v$ SPT
responses comparison, it is noticed that specimen deflection driven $F - u$ response seems stiffer.

![SPT Response for Mat 6](image)

**Fig. 5** Comparison of force-specimen deflection ($F - u$), and force-punch displacement ($F - v$) SPT responses

Therefore, the yield and ultimate strengths estimation may be erroneous as a result of numerous ambiguities that arise through inconsistent application of $F - u$ or $F - v$ SPT responses, estimation in elastic-plastic transition force, $F_e$, and accuracy of proclaimed best-fitting correlations. This prompts an opportunity to conduct a detailed investigation that is concentrated across acknowledged ambiguities.

### 6.4 Numerical Finite Element (FE) simulation driven SPT study

The objective of this study is to unveil insight into elastic-plastic behaviour during SP testing and establish reliable correlations/approaches to estimate uniaxial yield and ultimate strengths from derived $F - u$ or $F - v$ SPT responses. In an attempt to establish universal correlations, systematically 206 material datasets are designed per defined variations as mentioned in Table 3, which covers extreme ranges of elastic-plastic mechanical properties of general-purpose metallic materials. It is a cumbersome task to undergo traditional experimental small punch testing for such large sets of materials. Hence, the numerical FE simulation-driven approach is leveraged for this study.
6.4.1 FE methodology calibration

The SPT model and methodology need to be calibrated so that they match the competence of physical experimental testing in order to enhance users’ confidence. For such calibration exercises, the experimental results are referred from reputed literature [12],[13],[14],[15], including the experiment tests that we conducted using proprietary materials. These data are listed in Table 2.

As shown in Fig. 6, the FE-simulated SPT responses are compared with Table 2 outlined experimental test responses. These comparative curves are fittings well for most of the materials which endorse the accuracy of calibrated FE simulation SPT model and methodology. Such calibrated FE modelling practice is continued to follow during the course of FE simulation driven SPT study using Table 3 listed designed materials.

Table 2  Referenced SPT experimental input-output data

<table>
<thead>
<tr>
<th>Literature</th>
<th>$E$ (MPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\sigma_u$ (MPa)</th>
<th>$n$</th>
<th>$F_{ee}$ (N)</th>
<th>$F_m$ (N)</th>
<th>$u_m$ (mm)</th>
<th>$v_m$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI 65-45-12</td>
<td>1.80E+05</td>
<td>236</td>
<td>417</td>
<td>7.54</td>
<td>141.1</td>
<td>896.4</td>
<td>1.01</td>
<td>---</td>
</tr>
<tr>
<td>SS 316</td>
<td>2.00E+05</td>
<td>260</td>
<td>521</td>
<td>7.00</td>
<td>164.5</td>
<td>1844.8</td>
<td>1.65</td>
<td>---</td>
</tr>
<tr>
<td>GR91 steel [13]</td>
<td>2.00E+05</td>
<td>534</td>
<td>683</td>
<td>11.4</td>
<td>330.7</td>
<td>1507.5</td>
<td>1.33</td>
<td>---</td>
</tr>
<tr>
<td>SS 316L [14]</td>
<td>2.07E+05</td>
<td>388</td>
<td>577</td>
<td>6.81</td>
<td>64.84</td>
<td>474.8</td>
<td>0.82</td>
<td>---</td>
</tr>
<tr>
<td>X80 Pipeline [15]</td>
<td>2.00E+05</td>
<td>594</td>
<td>713</td>
<td>12.4</td>
<td>409.2</td>
<td>1960.9</td>
<td>1.75</td>
<td>---</td>
</tr>
</tbody>
</table>

6.4.2 Material data set

The elastic-plastic mechanical characteristics of any material are defined by the number of parameters, including young’s modulus, $E$, yield strength, $\sigma_y$, strain hardening exponent, $n$, ultimate strength, $\sigma_u$, ultimate strain, $e_u$. The assessment of damage characteristic exposure after ultimate strength is scoped out.

6.4.2.1 Sensitivity study

The sensitivity of material parameters may vary for SPT responses, so it is important to understand each parameter's sensitiveness. This sensitivity study will help to define the
weightings of each parameter to minimize the material dataset variances. A sensitivity severity concerning to material parameters is outlined in Fig. 7 (A), whereas Fig. 7 (B), highlights the sensitivity for SPT geometries. By following the outcome of Fig. 7 (A), and (B), the variation of material parameters and specimen thickness, \( h_0 \), are only included whereas other SP test apparatus geometrical specifications are followed in accordance with Table 1, EN 10371:2021 [5] while conducting detailed sensitivity analysis. The Poisson’s ratio and Young modulus are least sensitive as recognized by orange/yellow-toned sensitivity level closer to ZERO, in contrast to green-toned sensitivity levels for other sensible parameters.

![FEA V/S EXPERIMENTAL (F-u) RESPONSE](image)

**Fig. 6** Comparison of FE simulation v/s Experimental SPT responses

The SPT responses against key parameters are revealed that specimen thickness, \( h_0 \), yield strength, \( \sigma_y \), ultimate strength, \( \sigma_u \), and strain hardening exponent, \( n \), are the most sensitive parameters and Young’s modulus, \( E \) and Poisson’s ratio, \( \mu \) are the least sensitive to SPT responses. The four parameters, \( h_0, \sigma_y, \sigma_u, e_u \), are preferred for weighting while designing the most meaningful material datasets to expose the greatest accuracy. The material strain hardening exponent, \( n \) is captured with reference of ultimate strain, \( e_u \) by correlating it through Ramberg Osgood material model.
6.4.2.2 Designing of material datasets

While designing material datasets, the most extreme ranges of mechanical properties were covered in general, and their variations were based on the weightage realized through sensitivity study. Table 3 lists a total of 206 materials those were designed to innovate the best-fit correlations to estimate the mechanical strengths using $F - u$ and $F - v$ SPT responses. It is impractical to discuss the outcome for

listed all of the 206 designed materials so that arbitrarily 10 materials are chosen as reported in Table 4 to verify the accuracy of improved comprehensive correlations and discuss the shortcomings.

Table 3  Designed material datasets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Lower limit</th>
<th>Upper limit</th>
<th>Increment</th>
<th>Number of variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus (MPa)</td>
<td>$E$</td>
<td>2e5</td>
<td>2e5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>$\mu$</td>
<td>0.3</td>
<td>0.3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>$\sigma_y$</td>
<td>100</td>
<td>1500</td>
<td>20</td>
<td>71</td>
</tr>
</tbody>
</table>
Ultimate strength (MPa) \( \sigma_u \) 200 2000 15 121
Engg. strain (mm/mm) \( e_u \) 0.1 0.9 0.1 9
Initial specimen thickness (mm) \( h_0 \) 0.3 0.7 0.1 5

TOTAL 206

Table 4  Arbitrary material datasets

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Young’s Modulus (GPa)</th>
<th>Yield Strength (MPa)</th>
<th>Ultimate Strength (MPa)</th>
<th>Uniform elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAT-1</td>
<td>156</td>
<td>283</td>
<td>418</td>
<td>29</td>
</tr>
<tr>
<td>MAT-2</td>
<td>200</td>
<td>311</td>
<td>584</td>
<td>55</td>
</tr>
<tr>
<td>MAT 3</td>
<td>215</td>
<td>110</td>
<td>820</td>
<td>05</td>
</tr>
<tr>
<td>MAT 4</td>
<td>197</td>
<td>840</td>
<td>1300</td>
<td>15</td>
</tr>
<tr>
<td>MAT 5</td>
<td>180</td>
<td>150</td>
<td>230</td>
<td>7.5</td>
</tr>
<tr>
<td>MAT 6</td>
<td>200</td>
<td>1400</td>
<td>1800</td>
<td>90</td>
</tr>
<tr>
<td>MAT 7</td>
<td>197</td>
<td>478</td>
<td>750</td>
<td>84</td>
</tr>
<tr>
<td>MAT 8</td>
<td>176</td>
<td>546</td>
<td>950</td>
<td>42</td>
</tr>
<tr>
<td>MAT 9</td>
<td>176</td>
<td>1102</td>
<td>1500</td>
<td>23</td>
</tr>
<tr>
<td>MAT 10</td>
<td>160</td>
<td>598</td>
<td>1150</td>
<td>35</td>
</tr>
</tbody>
</table>

7  Achievements with respect to objectives

With reference of defined objectives, the mechanical strength estimation accuracy was assessed using the best practices proposed by recently published EN 10371:2021 [5] standard and later as described following, the comprehensive correlations are established and improved to enhance accuracy to estimate the conventional uniaxial mechanical strengths for the wider class of metallic materials which are exposed to 100-2000 MPa of strengths.

With reference of tabulated results in Table 6, Table 8, and Table 10, the mechanical strengths estimation enhanced for accuracy \( R^2 > 0.95 \), and error confinement to \( \pm 10\% \), irrespective of SPT practice and class of material to test. Earlier such accuracy varied for \( R^2 = 0.72-0.87 \) for particular class of materials even using the best practices recommended by recently published EN 10371:2021 [5] standard.
An intuitive software application is developed and made available for the community of practice via tinyurl.com/SPT-to-Uniaxial as shown in Fig. 8, to ensure consistent post-processing practice to convert SPT data into uniaxial strength estimations.

![Small punch test to uni-axial response convertor](image)

**Fig. 8** Small punch test to uni-axial response convertor

### 7.1 Yield strength correlation

The $F - u$ and $F - v$ SPT responses of Table 3 listed designed materials are evaluated through FE simulation, and the elastic-plastic transitioning yield forces, $F_{ee}$ and $F_{eA}$ are estimated by following various approaches.

A normalized equation can be written as Eq. (6)

$$\sigma_y = \beta_y \frac{F_e}{R_0^a}$$  \hspace{1cm} \ldots (6)

Where, $a$ is an exponent of specimen's initial thickness

The data fitting is verified according to EN 10371:2021 [5] suggested correlations while benchmarking of $\beta_y$ & $a$ values for the designed materials.

Subsequently, the SPT response data of designed materials are systematically analysed by means of prominent mathematical models and algorithms to formulate the improved & comprehensive best-fit correlations to be fit for any SPT response post-processing approach.
Table 5 $\beta_y$ & $\alpha$ values for multiple scenarios

| Literature | Force Response | Approach | Best-fit Constants $| \beta_y \alpha $ | Data-fit Accuracy $(R^2)$ | Material Application |
|------------|----------------|----------|------------------|---------------------------|-------------------------|
| EN 10371:2021 | $f(u)$ | $F_{ea}$ | 0.510 2.00 | 0.728 | Steels, $200 < \sigma_y < 1000$ |
| This study | $f(v)$ | $F_{ea}$ | 0.479 2.00 | 0.783 |
| | $f(u)$ | $F_{ea}$ | 0.23 2.62 | 0.978 |
| | $f(v)$ | $F_{ea}$ | 0.23 2.56 | 0.985 |
| | $f(u)$ | $F_{ee}$ | 0.32 2.41 | 0.983 |
| | $f(v)$ | $F_{ee}$ | 0.27 2.49 | 0.988 |

The yield strengths are estimated through improved correlations while adopting various approaches and compared as mentioned in Table 6. The derived means square error ($R^2$) for numerous data, conforms the authenticity of improved correlations for the yield strength estimation using $F - u$ and $F - v$ SPT responses of the universal class of metallic materials.

Table 6 Accuracy verification for estimated Yield strength, $\sigma_y$ using improved correlations

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_y$*</th>
<th>Estimated Yield strength, $\sigma_y$</th>
<th>Yield strength estimation error, $\sigma_y$%</th>
<th>$F_{ee f(u)}$</th>
<th>$F_{ee f(v)}$</th>
<th>$F_{ea f(u)}$</th>
<th>$F_{ea f(v)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAT 1</td>
<td>283</td>
<td>258 271 279 278</td>
<td>-9.0% -4.2% -1.3% -1.6%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT 2</td>
<td>311</td>
<td>268 270 273 277</td>
<td>-13.8% -13.3% -12.1% -10.9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT 3</td>
<td>110</td>
<td>146 156 155 164</td>
<td>32.3% 42.0% 40.9% 49.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT 4</td>
<td>840</td>
<td>808 819 802 827</td>
<td>-3.8% -2.5% -4.5% -1.5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT 5</td>
<td>150</td>
<td>126 125 134 134</td>
<td>-15.8% -16.7% -10.7% -10.6%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT 6</td>
<td>1400</td>
<td>1282 1322 1251 1304</td>
<td>-8.4% -5.6% -10.6% -6.9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT 7</td>
<td>478</td>
<td>490 459 491 468</td>
<td>2.5% -4.0% 2.8% -2.2%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT 8</td>
<td>546</td>
<td>569 532 562 535</td>
<td>4.3% -2.6% 2.9% -2.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT 9</td>
<td>1102</td>
<td>1034 1057 1014 1039</td>
<td>-6.2% -4.1% -8.0% -5.7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAT 10</td>
<td>598</td>
<td>590 600 595 597</td>
<td>-1.4% 0.3% -0.5% -0.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$R^2$ 99.4% 99.4% 99.7% 99.6%

* Referred from Table 4
7.2 Ultimate strength correlation

The forces relevant to ultimate strength, $F_m$ and $F_i$ are determined over the $F - u$ and $F - v$ SPT responses of the designed materials.

The normalized Eq. (7) and Eq. (8) equations,

$$\sigma_u = \beta_{um} \frac{F_{m}}{h_0 u_m} \quad ... \text{(7)}$$

$$\sigma_u = \beta_{ui} \frac{F_{i}}{h_0} \quad ... \text{(8)}$$

Where, $b, c, d$ are miscellaneous exponents, and $\beta_{um}, \beta_{ui}$ are constants

Similar to yield strength constants benchmarking, the ultimate strength estimating best-fit correlations $\beta_{um}, \beta_{ui}, b, c, d$ are systematically processed and improved as proposed in Table 7 and Table 9.

It was difficult to formulate the best-fit correlation to achieve the strength estimation accuracy $R^2 >0.95$ using $F_m$ based approach, therefore piece-wise correlations are defined as a function of ultimate strain, $e_u$.

The ultimate strengths are estimated through improved correlations while adopting $F_m$ based approach approaches and compared as mentioned in Table 8. The derived means square error ($R^2$) for numerous data, conforms the authenticity of improved correlations for the ultimate strength estimation using $F - u$ and $F - v$ SPT responses of the universal class of metallic materials.

However, another ultimate strength estimation approach based on the pseudo intersection point $F_i$, at onset of plastic instability has certain limitations. Although, improved correlations enhances data-fitting accuracy ($R^2$) from ~0.60 to ~0.95 with reference of Table 10, data estimation error prevails in the range of 20-40%. Such deviation is primarily driven by using normalized $u_i/v_i$ [41], which is adversely impacting $F_i$ based correlation to be complied for the universal class of materials. Therefore $F_m$ based approach seems quite intuitive for ultimate strength estimation as compared to $F_i$ based approach.
Table 7  \( \beta_{um}, b & c \) values for \( F_m \) based approach

<table>
<thead>
<tr>
<th>Literature</th>
<th>Force Response</th>
<th>Best-fit Constants</th>
<th>Data-fit Accuracy ((R^2))</th>
<th>Application</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 10371:2021</td>
<td>( f(u) )</td>
<td>0.278 1.00 1.00</td>
<td>0.747</td>
<td>---</td>
<td>Steel [13],[41],[42]</td>
</tr>
<tr>
<td></td>
<td>( f(u) )</td>
<td>0.18 0.14 1.21</td>
<td>0.999</td>
<td>5% &lt; ( e_u ) &lt; 28%</td>
<td></td>
</tr>
<tr>
<td>This study</td>
<td>( f(u) )</td>
<td>0.16 0.27 1.24</td>
<td>0.999</td>
<td>28% &lt; ( e_u ) &lt; 50%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( f(v) )</td>
<td>0.14 0.32 1.18</td>
<td>0.999</td>
<td>( e_u ) &gt; 50%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( f(v) )</td>
<td>0.19 0.11 1.21</td>
<td>0.999</td>
<td>5% &lt; ( e_u ) &lt; 15%</td>
<td></td>
</tr>
</tbody>
</table>

Table 8  Ultimate strength, \( \sigma_{um} \) estimation using improved correlations

<table>
<thead>
<tr>
<th>Material</th>
<th>( F_m )</th>
<th>( d_{uf(u)} )</th>
<th>( d_{uf(v)} )</th>
<th>( \sigma_{umf(u)} )</th>
<th>( \sigma_{umf(v)} )</th>
<th>( \sigma_u^* )</th>
<th>( \text{Err} ) ( \sigma_{umf(u)} )</th>
<th>( \text{Err} ) ( \sigma_{umf(v)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAT 1</td>
<td>1161</td>
<td>1.38</td>
<td>1.55</td>
<td>402</td>
<td>408</td>
<td>418</td>
<td>-3.8%</td>
<td>-2.4%</td>
</tr>
<tr>
<td>MAT 2</td>
<td>1764</td>
<td>1.61</td>
<td>1.82</td>
<td>587</td>
<td>613</td>
<td>584</td>
<td>0.4%</td>
<td>5.0%</td>
</tr>
<tr>
<td>MAT 3</td>
<td>1894</td>
<td>1.37</td>
<td>1.51</td>
<td>755</td>
<td>795</td>
<td>820</td>
<td>-8.0%</td>
<td>-3.0%</td>
</tr>
<tr>
<td>MAT 4</td>
<td>3221</td>
<td>1.39</td>
<td>1.54</td>
<td>1282</td>
<td>1350</td>
<td>1300</td>
<td>-1.4%</td>
<td>3.8%</td>
</tr>
<tr>
<td>MAT 5</td>
<td>546</td>
<td>1.42</td>
<td>1.56</td>
<td>216</td>
<td>229</td>
<td>230</td>
<td>-5.9%</td>
<td>-0.6%</td>
</tr>
<tr>
<td>MAT 6</td>
<td>6910</td>
<td>1.48</td>
<td>1.69</td>
<td>1933</td>
<td>1982</td>
<td>1800</td>
<td>7.4%</td>
<td>10.1%</td>
</tr>
<tr>
<td>MAT 7</td>
<td>2790</td>
<td>1.54</td>
<td>1.75</td>
<td>771</td>
<td>790</td>
<td>750</td>
<td>2.8%</td>
<td>5.4%</td>
</tr>
<tr>
<td>MAT 8</td>
<td>2845</td>
<td>1.42</td>
<td>1.61</td>
<td>978</td>
<td>989</td>
<td>950</td>
<td>2.9%</td>
<td>4.1%</td>
</tr>
<tr>
<td>MAT 9</td>
<td>3964</td>
<td>1.39</td>
<td>1.56</td>
<td>1576</td>
<td>1389</td>
<td>1500</td>
<td>5.1%</td>
<td>-7.4%</td>
</tr>
<tr>
<td>MAT 10</td>
<td>3300</td>
<td>1.42</td>
<td>1.61</td>
<td>1134</td>
<td>1147</td>
<td>1150</td>
<td>-1.4%</td>
<td>-0.3%</td>
</tr>
</tbody>
</table>

\( R^2 \) 99.4% 98.2%

* Referred from Table 4
### Table 9 \( \beta_{ui} \), & \( d \) values for \( F_i \) based approach

<table>
<thead>
<tr>
<th>Literature</th>
<th>Force Response</th>
<th>( u_i/v_i ) (mm)</th>
<th>( \beta_{ui} )</th>
<th>( d )</th>
<th>Data-fit Accuracy ( (R^2) )</th>
<th>Material Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 10371:2021</td>
<td>( f(u) )</td>
<td>0.552</td>
<td>0.192</td>
<td>2.00</td>
<td>0.580</td>
<td>Ferritic/Martensitic steels [41]</td>
</tr>
<tr>
<td></td>
<td>( f(v) )</td>
<td>0.645</td>
<td>0.179</td>
<td>2.00</td>
<td>0.659</td>
<td></td>
</tr>
<tr>
<td>This study</td>
<td>( f(u) )</td>
<td>0.552</td>
<td>0.13</td>
<td>2.85</td>
<td>0.952</td>
<td>Steels,</td>
</tr>
<tr>
<td></td>
<td>( f(v) )</td>
<td>0.645</td>
<td>0.13</td>
<td>2.74</td>
<td>0.961</td>
<td>200 &lt; ( \sigma_u ) &lt; 2000</td>
</tr>
</tbody>
</table>

### Table 10 Ultimate strength, \( \sigma_{ui} \) estimation using improved correlations

<table>
<thead>
<tr>
<th>Material</th>
<th>( F_{f(u)} )</th>
<th>( F_{f(v)} )</th>
<th>( u_i )</th>
<th>( v_i )</th>
<th>( \sigma_{ui f(u)} )</th>
<th>( \sigma_{ui f(v)} )</th>
<th>( \sigma_u^* )</th>
<th>( \text{Err} ) ( - \sigma_{ui f(u)} )</th>
<th>( \text{Err} ) ( - \sigma_{ui f(v)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAT 1</td>
<td>583</td>
<td>633</td>
<td>0.55</td>
<td>0.65</td>
<td>543</td>
<td>550</td>
<td>418</td>
<td>30%</td>
<td>32%</td>
</tr>
<tr>
<td>MAT 2</td>
<td>574</td>
<td>619</td>
<td>0.55</td>
<td>0.65</td>
<td>538</td>
<td>538</td>
<td>584</td>
<td>-8%</td>
<td>-8%</td>
</tr>
<tr>
<td>MAT 3</td>
<td>939</td>
<td>1031</td>
<td>0.55</td>
<td>0.65</td>
<td>874</td>
<td>895</td>
<td>820</td>
<td>7%</td>
<td>9%</td>
</tr>
<tr>
<td>MAT 4</td>
<td>1640</td>
<td>1734</td>
<td>0.55</td>
<td>0.65</td>
<td>1526</td>
<td>1506</td>
<td>1300</td>
<td>17%</td>
<td>16%</td>
</tr>
<tr>
<td>MAT 5</td>
<td>300</td>
<td>328</td>
<td>0.55</td>
<td>0.65</td>
<td>279</td>
<td>285</td>
<td>230</td>
<td>21%</td>
<td>24%</td>
</tr>
<tr>
<td>MAT 6</td>
<td>2775</td>
<td>3003</td>
<td>0.55</td>
<td>0.65</td>
<td>2583</td>
<td>2608</td>
<td>1800</td>
<td>44%</td>
<td>45%</td>
</tr>
<tr>
<td>MAT 7</td>
<td>1150</td>
<td>1241</td>
<td>0.55</td>
<td>0.65</td>
<td>1070</td>
<td>1078</td>
<td>750</td>
<td>43%</td>
<td>44%</td>
</tr>
<tr>
<td>MAT 8</td>
<td>1256</td>
<td>1347</td>
<td>0.55</td>
<td>0.65</td>
<td>1169</td>
<td>1170</td>
<td>950</td>
<td>23%</td>
<td>23%</td>
</tr>
<tr>
<td>MAT 9</td>
<td>1973</td>
<td>2134</td>
<td>0.55</td>
<td>0.65</td>
<td>1836</td>
<td>1853</td>
<td>1500</td>
<td>22%</td>
<td>24%</td>
</tr>
<tr>
<td>MAT 10</td>
<td>1451</td>
<td>1565</td>
<td>0.55</td>
<td>0.65</td>
<td>1350</td>
<td>1359</td>
<td>1150</td>
<td>17%</td>
<td>18%</td>
</tr>
</tbody>
</table>

\( R^2 \) 95.9% 95.7%

* Referred from Table 4

### 8 Conclusion

The achievement conceded through this research study, it is noticed that the improved SPT correlations estimate the preserved mechanical strengths with accuracy \( R^2 > 0.95 \), and error confinement to \( \pm 10\% \), irrespective of SPT practice and class of material utilized which shows the significantly improved accuracy as compared to recently published British standard EN 10371:2021 [5]. These virtuous of improved correlations make them quite comprehensive in
nature for the mechanical characterization of in-service systems. This is how the hereby study brings distinct value addition and confidence. Although strengths estimation accuracy can be secured by adopting improved correlations, a user must be conscious to follow appropriate practices for SPT data post-processing. An intuitive software application is developed and made available for the community of practice via tinyurl.com/SPT-to-Uniaxial, to ensure consistent post-processing practice to convert SPT data into uniaxial strength estimations.

9 List of publications


10 References


313–316.


[34] J.D. Parker, A. McMinn, J.R. Foulds, Material Sampling for the Assessment of Component Integrity, T.V. Narayanan et Al. (Eds.), American Society of Mechanical


