

Web Driven Strength of Materials Database and Modelling Tool (StreMa-DB)

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Abstract— *Aiming at developing a flexible IT tool that will enable someone to have fast access to strength and other useful properties of structural damageable materials by using appropriate queries through the internet, we have developed a relational web driven database accompanied by a modeling tool that is developed in Mathworks Matlab®. The database and the accompanying matlab tool aims at fast approximate calculations of the behavior of a certain structural material element under a given hazard intensity or under repeated cycles of loading.*

Index Terms— Failure model, Relational materials database, Web application for materials

I. INTRODUCTION

Civil construction structures such as buildings, bridges, pavements, tunnels and other subsurface engineering structures, dams, retaining walls, and the like are materials-intensive: the cost of the material dominates the product cost, and the quantity used is enormous. Then only the cheapest of materials qualify, and the design must be adapted to use them [1]. As was noted already in ancient years, materials, of themselves, affect us little; it is the way we use them which influences our lives (*from the Greek stoic philosopher Epictetus, AD 50–100, Discourses Book 2, Chapter 5*). Hence, from the earliest times when people started to build, it was found necessary to have information regarding the stiffness and strength of structural engineering (artificial) and earth (natural) materials so that rules for determining safe dimensions of structural members could be drawn up. This is the so called “forward problem”, namely the selection of proper structural materials under given specifications. The “backward problem” pertains to the estimation of durability of exposed engineering materials against a given hazard or simply the remaining life or the forensic analysis of occurred premature structural failures, e.g. Fig. 1.

Several World Wide Web (www) or simply web driven relational databases have been developed in an effort to collect the available mechanical and physical data on artificial and natural structural engineering materials. For example, MatWEB (<http://www.matweb.com>), NIMS Materials Database (<http://mits.nims.go.jp>) containing more than 30,000 materials, and MATBASE (<http://www.matbase.com>), are some examples of such databases. Databases for natural materials such as rocks usually focus on geological and mineralogical information (e.g., petrographic data, mineral composition, and microstructure). Mindat

(<http://www.mindat.org>) is an example of such a database. Also, some engineering databases specialized for rocks have been developed. For example, the program RockPro, developed by ESG Solutions (<http://www.esg.ca>) in Canada, is a rock mechanics database tool for recording, analyzing and reporting microseismical measurements. This program is dedicated to data recording for specific projects, including support evaluations, rock bursts, and rock pillar performance. A more general rock mechanics database that stores mechanical parameters for rocks is the RocProp Properties Database developed by RocScience (<http://www.rocsience.com>). This database currently contains over 700 test records only for rocks. Each record includes basic information about the rock (rock type, country, location, unit weight, etc.), reference information, and the actual test data. It could also be used for parameter identification of rocks obeying the two dimensional Hoek-Brown and Mohr-Coulomb failure models.

Despite of all these developments in data storage of material properties, there is a lack of material failure models and methods of their calibration for subsequent use with two or three dimensional numerical simulation tools aiming at static (monotonic or cyclic) and dynamic analyses and forward vulnerability analyses or back-analyses of premature failures (that is called “forensic analysis”) of materials and structures in urban spaces. Towards this aim, a new web driven materials database called StreMa-DB (an acronym coined from “Strength of Materials Database”) has been developed and is briefly presented here.



Fig. 1 Collapse down to its foundations of the Bayram hotel during the second earthquake of Mw=5.7 in the city of Van (Turkey) on 9 November 2011 (courtesy of E. Lekkas).

It may help to increase quality, innovate, optimize structural engineering materials decisions (at the design or damage assessment phases), save cost and time, and reduce premature failure risk of engineering constructions in urban areas. This is illustrated by an example use case displayed in Fig. 2. The user maps the typologies of buildings and each structural or building material like in the example of Fig. 2a referring to Piazza della Signoria in Firenze, Italy. The necessary properties of these materials evaluated from lab tests are stored in the database and processed for assigning the most appropriate mechanical or failure model to each material with parameters calibrated on the experimental tests. This set of data subsequently may feed a static or dynamic numerical code that is engaged for the estimation of damage distribution in the area after the application of a hazard of given intensity (i.e. earthquake of a given magnitude) or for the purpose of checking the compatibility of new materials used for renovation with the monumental ones against the application of some mechanical load (like for example an earthquake or explosion at a specific location and given intensity and duration).

In Fig. 1 it is shown the collapse of an apparently rigid hotel during the consecutive Van earthquake. It is recalled that the first earthquake of Mw 7.2 occurred on 23 October 2011 whereas the second one with Mw 5.7 happened on 9 November 2011. The hotel collapse incident was not caused due to design structural deficiencies of the building, but due to damage inherited in its concrete elements (columns, beams, slabs etc) from past aging mechanisms (weathering, past earthquakes). Hence, at least one of the “weaknesses” of the city was the not-in-time and inappropriate inspection of aging buildings. This type of weakness (e.g. inherited damage) could be assessed by a set tools in a toolbox. One of the tools is a database like StreMa-DB with a built-in dedicated project e.g. “Damage assessment in the city of VAN” for example as is explained in the next Section II devoted to the description of the structure of the database. This IT tool could be also used by local engineers (inspectors), the civil protection agency of a city, insurers etc. to keep a track on the aging (damage) of structural materials (i.e. concrete, steel or other material) in exposed buildings or other structures in the city (e.g. Fig. 2). The FCMODEL application accompanying the database is also a complementary tool of StreMa-DB, build in Matlab®, that could be used for quick assessments of structural integrity under imposed stresses anticipated during an earthquake. The database may directly export stored test data into the FCMODEL application, which is able to quickly evaluate the prediction/response of several failure criteria. under imposed stresses anticipated during an earthquake. Another tool of the toolbox in such a project could be a portable instrument for damage assessment of structural materials (like ultrasonic, micro drilling, hardness devices etc) that are available in the market.

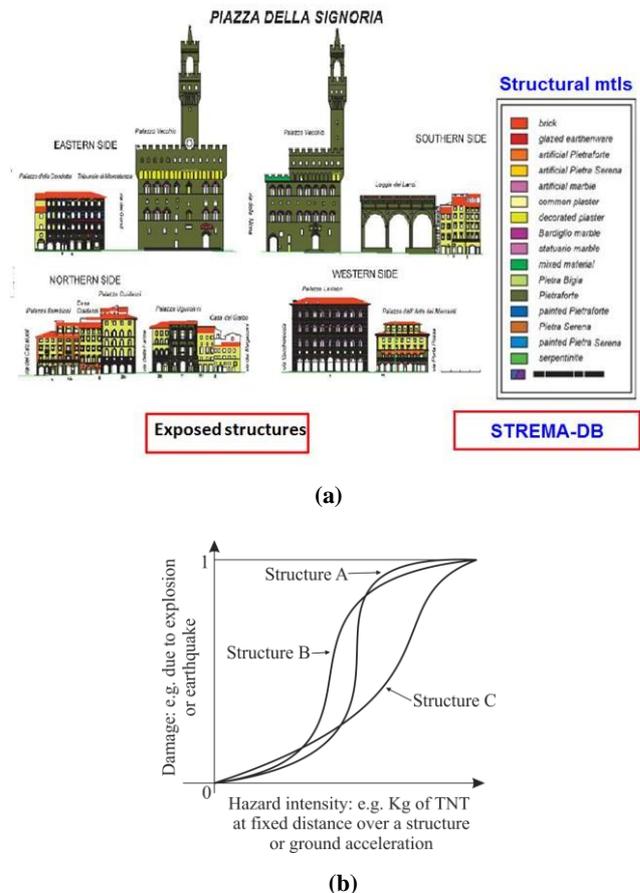


Fig. 2. Example use case of Piazza della Signoria in Firenze, Italy: (a) mapping of the typologies of buildings and each structural or building material, (b) damage response curves of different materials.

II. MAIN FEATURES OF STREMA-DB

A. Architectural aspects of the database

The main objective in the creation of this database is to implement structural engineering materials (artificial and natural) data management in a single and searchable resource. Also, to deliver structural engineering materials data and most importantly their identified strength parameters to the people that use them (i.e. risk modelers, vulnerability of exposed element to natural or technological hazards modelers, designers of engineering structures etc), on their computer. In addition, in order to give the ability to someone to select structural engineering materials suitable for a given application based on given design specifications, a dedicated search module that could be enriched with a penalty or objective function has been developed.

The following five classes of engineering structural materials are considered in the database: (1) woods, (2) rocks/soils, (3) glasses, (4) concretes/ceramics, (5) metals/alloys. The main innovations of this database are:

- a) It includes the FCMODEL matlab tool for the calibration of yield and/or failure criterion among a set of established criteria applicable for a range of brittle and ductile

materials like the above belonging to the five classes. The calibration is based on the test data stored in the database. The database and FCMODEL are linked together through a web application that may export yield/damage/failure data to be used into Matlab[®]. Failure models are attached in the FCMODEL code as modules. Thus new modules may be attached without changing the core application. Note that yield/damage/failure are surfaces in the three dimensional principal stress space that if reached by the stress vector the material yields, damages, and fails, respectively.

- b) Another innovative item is that the user may implement models for damageable (aging) materials. In this case data obtained from cyclic (low or high cycle) fatigue tests are stored and subsequently processed. This may be done since cyclic test data may be inserted directly in the database or attached to it in the form of *.txt* or *.xls* files that are amenable of subsequent processing.
- c) The materials in StreMa-DB are organized by projects. Each project is dedicated for a specific purpose based on types of materials, types of structural applications, etc.

The main database structure has been developed in SQL (particularly MySQL was employed as a Relational Database Management System [RDBMS]). Additional experiment (test) types may be implemented as additional tables (modules) into the database. Thus the database is highly extensible in this direction. The materials in the database are organized by projects. Fig. 3 illustrates an abstract relational diagram of the database that captures its main structure/functionality. The connecting relations between the several parts of the database are marked with straight lines. On every connection line the type of the relation is also illustrated. A one-to-one relation is marked as 1:1 while 1:n means a one-to-many relation. The users are assigned to projects through the Role Based Access Control (RBAC). Thus a project may contain several users with different roles (simple viewers, editors/members, managers etc) while every user may be assigned in many projects. On the other hand, every project contains several materials. For each material there are available modules that may be enabled or disabled. The connections between the materials and their respective enabled modules are controlled by the web application. Thus, a connection between a material and a module is active only if the respective module is enabled. Currently, two modules have been implemented: 1) the “Mechanical Properties” module which is a list of mechanical properties that characterize the material, and 2) the “Standard Tests” module which stores typical mechanical tests that were performed on this material. From the latter module the web application may export the failure/yield stresses of all the stored experiments. This exported data may be used directly by the accompanying FCMODEL application in Matlab for further processing. Every Material contains fundamental information, like origination, manufacturing, structural applications, chemical composition, suppliers and indicative unit price. In addition relevant images of the material referring to appearance, commercial applications, color, texture, microstructure etc, are also included. It also contains basic physicomechanical

Properties of the material like density, porosity, grain size etc as is illustrated in Fig. 4a, and strength properties including elastic properties and fracture toughness as is demonstrated in Fig. 4b.

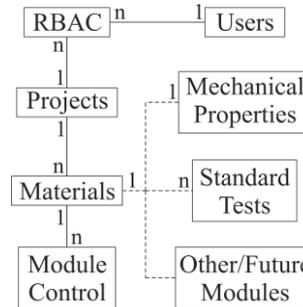


Fig. 3. Abstract relational diagram of StreMa-DB.

View Material: Cervaiolo Marble

Name	Cervaiolo Marble
Type	Marble
Classification	Metamorphic rock (Rocks & Soils)
Origin	Carrara, Italy
Commercial Apps	Is suitable for inner and external use. It can be applied for external coverings, above all for coverings of facades for palaces, buildings.
Unit Price	
Comments	Calcitic marble with xenoblastic microstructure, and its grain boundaries are mainly sutured. The crystal size is variable (150-200 μm) and the shape of crystals is anedral. Crystalline rock. The XR diffractometric analysis reveals the presence of dolomite. Dolomite has been evidenced in the thin section by the big dimension (300 μm) and by the toudious aspect. This marble shows a slight crystal orientation.
Density (Kg/m ³)	2710.00
Total Porosity (per unit volume)	0.013
Open Porosity (per unit volume)	0.004
Min Grain Size (m)	1.500e-4
Mean Grain Size (m)	2.000e-4
Max Grain Size (m)	3.000e-4
Permeability (m ²)	Not set
Thermal Conductivity (W/(m.K))	1.300e+0
Thermal Expansion Coefficient (1/K)	1.000e-3
References	
Create Time	2013-07-02 14:03:01
Create User	George Xiroudakis
Update Time	2013-09-14 19:24:55
Update User	George Exadaktylos

(a)

Mechanical Properties

Uniaxial Compression Strength (Pa)	-1.146e+8
Uniaxial Tension Strength (Pa)	-9.400e+6
Young Modulus (Pa)	6.350e+10
Poisson Ratio	2.900e-1
Cohesion	2.960e+7
Friction Angle (degrees)	36.40
Fracture Toughness (Pa ^m ^{0.5})	1.300e+6
Yield Stress (Pa)	Not set

(b)

Fig. 4. Screenshot of (a) basic descriptive and physical properties, and (b) strength properties of a structural material (a certain variety of Carrara marble of “statuario” quality.

The user may easily edit and import properties and images of materials and associated applications in the database through simple operations. In addition, for every Material there are available Modules that may be enabled or disabled. “Mechanical Properties” and “Standard tests” are the two Modules that have been already installed. The latter module

refers to standard monotonic or cyclic tests like uniaxial and triaxial compression, true triaxial compression/extension, uniaxial extension and indirect tension test (e.g. bending) that provide necessary data for subsequent calibration of appropriate failure model and parameter identification that is necessary for input into numerical codes. In addition, raw or processed experimental test data may be imported in the form of a .txt or .xls file. This gives the ability to further process the stored experiments with models that are not included currently in the FCMODEL application. There is, also, the possibility to add more modules in StreMa-DB depending on the desired application in the future. For example impact test results for glass, or Hardness, Shrinkage, and Rupture Strength for wood, or dedicated soil mechanics tests for soils etc, depending on the needs of the application.

Specialized tests that assess the materials degradation may, also, be implemented. As example we may refer to the micro-drilling test that may capture the surface damage of the materials. This test has been included in the previous Rock Mechanics Database developed by the authors [2].

Apart from the failure stress, the StreMa-DB stores also the number of cycles necessary to reach this stress, hence it can capture the fatigue curve of a material, i.e. the dependence of magnitude of the cyclic stress on the number of cycles. Hence, one may use the database to store also fatigue testing data. This set of data could be used to calibrate a fatigue model based on the concept of the “integrity function” also called “continuity function” which is a positive monotonically decreasing function, i.e. $\psi > 0$, $0 \leq \psi \leq 1$. For undamaged material, $\psi = 1$. At complete fracture $\psi = 0$. According to the above concept the evolution of the strength of a material denoted here by the symbol I with cycle N and a value I_0 at $N=0$ is as follows

$$I = I_0 \cdot \psi \tag{1}$$

Based on fundamental Fracture Mechanics principles an exponential fatigue model may be formulated as follows

$$\psi = A + (I - A) e^{-\lambda N} \tag{2}$$

where A , λ are positive constants and N is the number of ageing cycles. In addition, as a measure of material durability, the ‘half-life’ $N_{1/2}$ of the material can be defined as the number of cycles necessary to reduce the integrity to half its value may be easily obtained in the following manner

$$N_{1/2} = -\frac{\ln\left(\frac{2A - I}{2(A - I)}\right)}{\lambda} \tag{3}$$

The regression analysis of model (2) on experimental data of titanium subjected to high-cycle fatigue that are stored in StreMa-DB in the form of an .xls file, and particularly in the

“Standard Test” module, in order to calibrate the two-parameter model is shown in Fig. 5 below.

B. Web application tool

Besides the database, a web application was developed. It controls the database and permits an easy and quick access to the stored data. As is illustrated in the conceptual model shown in Fig. 6, a PHP web application has been developed to access the database.

In contrast of the previous Rock Mechanics Database developed by the authors [2], the materials in StreMa-DB are organized by projects. Each project is dedicated for a specific purpose; for example, one project may be dedicated to the Decorative and Building Stone Sector (i.e. selection of white marbles obeying certain aesthetical, physical and strength specifics), another for the Metallic Structures Sector (that is to say selection of metals and their alloys satisfying certain fatigue resistance specifications) or for the earthquake resilience of a city as was mentioned previously etc. The web application uses the Model-View-Controller approach [MVC] [3,4]. All the business logic is performed in the Models. The Views are the web pages displaying the data. The Controllers coordinate the interaction between the user and the Models/Views. The web application uses a Role Based Access Control [RBAC] approach and supports four different types of users: Administrators, Managers, Members and Readers. Readers may only read data in the Projects that they have access. Members inherit Readers’ rights and may also write data in these projects. Managers inherit Members’ rights plus create Projects. Finally, Administrators may also assign Managers. The database rests currently on <http://minelab.mred.tuc.gr/stremadb> and may be used by a limited group of users. It is our aim to disseminate it in the near future.

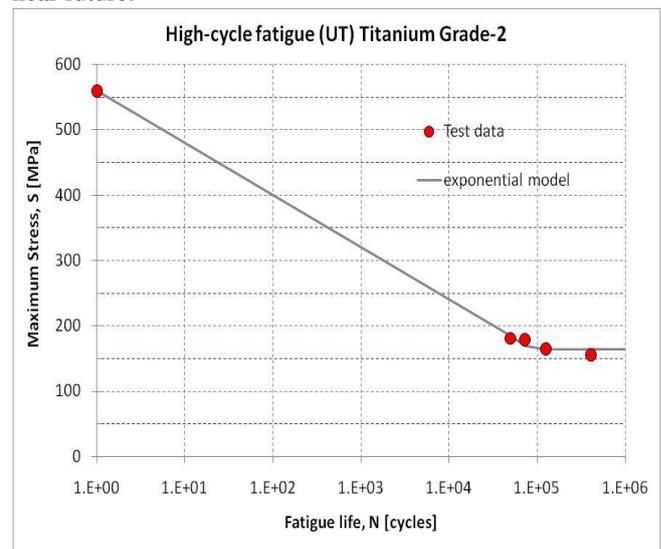


Fig. 5. Regression analysis of high cycle fatigue data of Titanium grade-2.

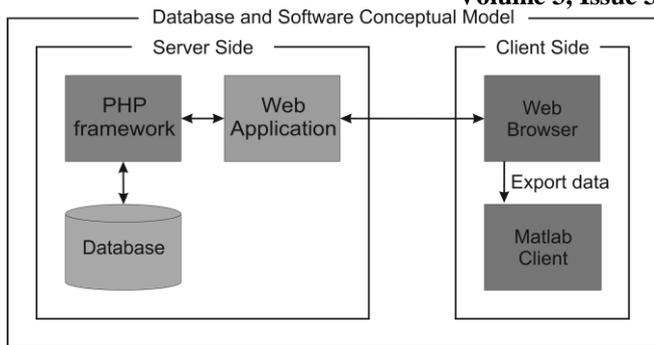


Fig. 6. Database and tool conceptual model

C. Search module with criteria/constrains

A search module with criteria/constrains has been also implemented into the database. This module works as a filter in the available stored materials with practically an infinite number of constraints. The user sets the desirable constraint list and the search module returns (filters) only the materials that satisfy the criteria. Thus, the user may select the best material that fits his/her use case.

For example the user may search for metals (1st constraint) with density below some value (2nd constraint) and Young’s modulus above some other value (3rd constraint). Or as another example the user may search for marbles (1st constraint) from a specific origin/country (2nd constraint), high (above some value) uniaxial compression strength (3rd constraint) and low cost (4th constraint). Practically the search module supports an infinite number of constraints that may help the user locate the exact material that suits his/her case.

To further enhance the Search Module, a “Penalty function” is under development. With this function the user will be able to insert weights in the desired criteria (in other words to set the relative importance of each criterion). Then, on every material that satisfies the constraints, a penalty score will be assigned according to the weights and the materials will be ranked according to this score. Thus, the user will be able to select the best material for his use case, given the importance of each constraint.

III. MATERIAL FAILURE MODEL CALIBRATION

FCMODEL is a Matlab[®] application that is used for the calibration of yield or failure criteria based on experimental data that may be drawn from StreMa-DB. Hence it exploits its full-featured technical computing environment. Several build-in failure criteria are included in this application. Note that yield or failure models are surfaces in the 3-dimensional principal stress space that if reached by the stress vector when the material yields or fails, respectively. Failure models are attached in the Matlab code as modules. Thus new modules may be attached without changing the core application. FCMODEL application has been developed in Matlab 7.12.0 (R2011a) with Optimization Toolbox. Thus, for Matlab’s versions R2011a and later it will execute as expected. It is noted that the Optimization Toolbox must, also, be installed.

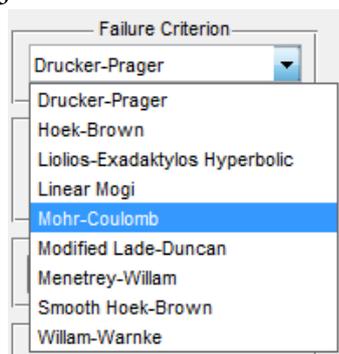


Fig. 7. Failure Criterion drop down menu

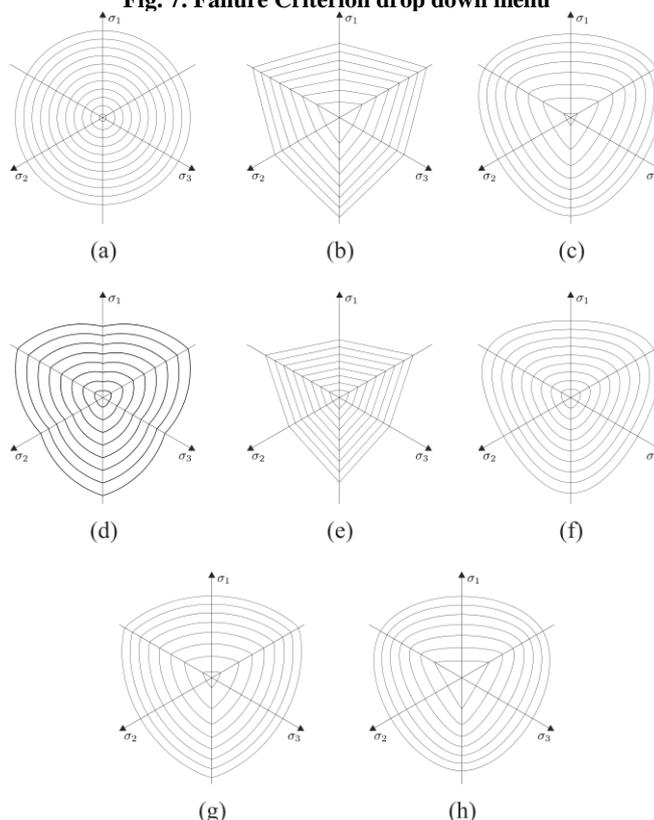


Fig. 8. Traces of failure models on the deviatoric plane: (a) Drucker-Prager, (b) Hoek-Brown, (c) Liolios-Exadaktylos, (d) Linear Mogi, (e) Mohr-Coulomb, (f) Modified Lade-Duncan (by Ewy), (g) Menetrey-Willam, (h) Willam-Warke.

The FCMODEL application may even run in older versions of Matlab but its behavior cannot be guaranteed. The *Failure Criterion* drop down menu contains the available failure criteria (Fig. Error! Reference source not found.7). The traces of these models on the deviatoric plane of the Heigh-Westergaard principal stress space are shown in Fig. 8. It is noted that any new failure criterion or model provided by the user will appear in this list of Fig. 7.

The Data File panel is used to open the file from StreMa-DB that contains the experimental data. A data file must be always selected before trying to calibrate a failure model. The data file must be in plain ASCII format (simple text file). Only .dat and .txt files are allowed. The file must contain three columns representing the three experimental principal stresses at failure. The three columns must be separated by the comma symbol “,”. Each row in the file

represents an experimental point. The first column represents the principal stress σ_1 , the second column the principal stress σ_2 and the third the principal stress σ_3 . The file must contain only the values of the experimental points and not any heading/tailing rows describing the columns etc.

The *Calibration Results* panel (Fig 9) displays the calibrated parameters after a successful calibration. The first group of two numbers in the screenshot of Fig. 9 represents the calibrated parameters of the selected model. The second group of numbers correspond to the Uniaxial Compression Strength (UCS), the Uniaxial Tensile Strength (UTS) and the Biaxial Compression Strength (BCS) predicted by the calibrated model. The third group of numbers refers to the Sum of Squared Residuals (SSR) and the Exit Flag of the non-linear least squares trust region reflective algorithm. A good fit/calibration corresponds to low SSR value. FCMODEL uses Matlab's *lsqcurvefit* algorithm to minimize the objective function. The possible Exit Flag values and their interpretation are the following:

- 1 Algorithm converged to a solution.
- 2 Change in failure criterion parameters too small.
- 3 Change in SSR too small.
- 4 Computed search direction too small.
- 0 Too many function evaluations or iterations.
- 1 Stopped by output/plot function.
- 2 Bounds are inconsistent.
- 3 Regularization parameter too large (Levenberg-Marquardt).
- 4 Line search failed.

The plot options that are available only after a successful calibration are illustrated in Fig. 10. The application is able to plot the *Failure Surface*, the *Deviatoric Plane*, the *Meridional Plane*, the *Rendulic Plane*, the $\sigma_2 - \sigma_3$ plane, the *Residuals Polar Diagram* and the *Residuals Histogram*. More details on these plots as well as on the failure criteria implemented in the database may be found in [5,6]. For example as is demonstrated in Fig. 11 the *Failure Surface* option plots the calibrated failure surface, as well as the experimental points for a concrete material.

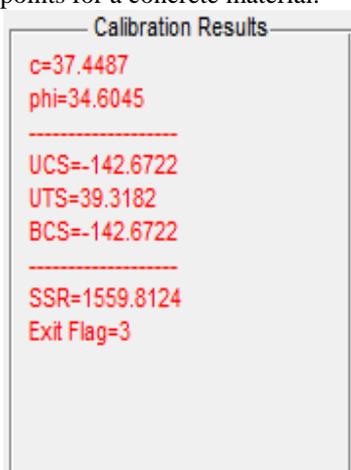


Fig. 9. Calibration Results panel

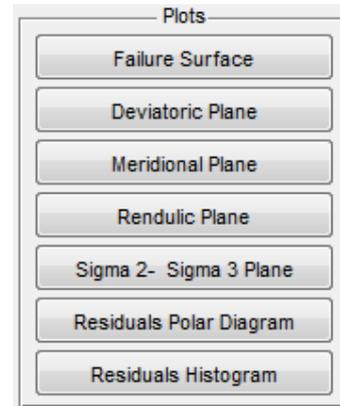


Fig. 10. Plots panel

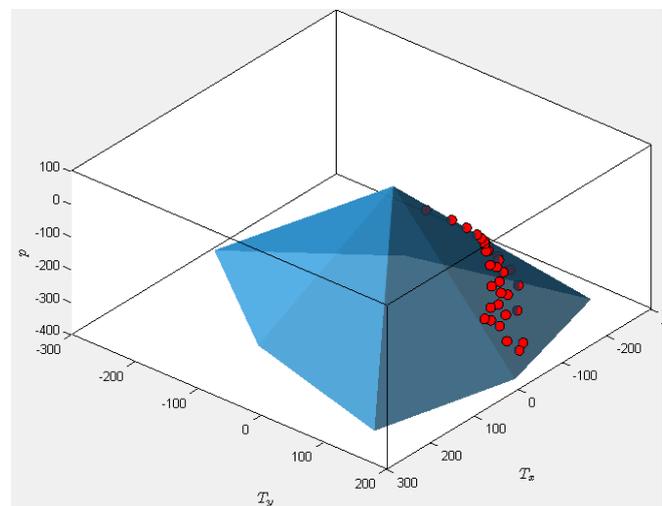


Fig. 11. Failure Surface plot (p is the mean pressure, $T_x = T \sin \theta$ and $T_y = T \cos \theta$, where T is the octahedral shear stress and θ is the Lode angle).

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Development of Relational Databases for Geomaterials. He has published several articles in International Scientific Journals and Referred Conferences. On June 2005, he participated, as member of the Local Organizing Committee, in the organization of the *7th International Workshop on Bifurcations, Instabilities and Degradation in Geomechanics* (Chairmen Prof. I. Vardoulakis and Prof. G. Exadaktylos).

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Georgios Exadaktylos has been born on 20th of December 1961. He has obtained his diploma of Mining & Metallurgical Engineering at the National Technical University of Athens in 1985. Next, in 1988 he has obtained a Master of Science Diploma in Mineral Resources Engineering from the Virginia Polytechnic Institute and State University (VPI&SU), USA. In the next year 1989, he has acquired the degree of Doctor of Philosophy in Mining Engineering and Rock Mechanics at the National Technical University of Athens. Currently he is Professor of Rock Mechanics & Mining Engineering at the Technical University of Crete (since 2004) and Director of the Mining Engineering Design Laboratory (since 1999). He is a member of more than ten professional bodies and member of the Editorial Board of four scientific journals. His expertise acquired from diverse studies and practical experience refers to Tunnelling, Surface and Underground Engineering, Rock and Soil Mechanics & Rock Physics, Geological & Geotechnical Engineering, Mineral resources exploration and evaluation, Geostatistics, Mining Engineering, Recovery-Storage of Energy-Natural Resources, Continuum Micromechanics, Fracture Mechanics, Damage Mechanics, Computational Mechanics, and Natural/Technological Hazards Engineering. He has published more than one hundred (100) papers in Greek & International scientific Journals, refereed national and international conferences, and book chapters. He is also the editor together with I. Vardoulakis of a book entitled *Bifurcation, Instabilities and Degradation in Geomechanics*, Springer. Apart from conducting applied research in a number of national projects funded by the private quarrying and mining sectors, he was also scientific and administrative responsible in ten competitive collaborative RTD European Projects of Framework Programmes (FP's) 4th to 7th. He has also been Project Coordinator in two European Commission collaborative RTD Projects in the areas of Rock and Fracture Mechanics and Rock Physics related to Protection of Cultural Heritage, and Work-Package leader referring to "*Tunneling Design and Ground Characterization*" in the largest European Commission IP-FP6 Project in Tunneling ever. In the year 2010 he has been also nominated as an Expert of INSPIRE EC-Directive in the Technical Committee of "Natural Risk Zones". In the period 2011–2012 he has been appointed by European Commission as an Expert Reviewer of proposals referring to large scale CO₂ storage.

Dr Pantelis Liolios was born on August 23rd, 1978. On February 2002, he obtained his Diploma of Mineral Resources Engineer at Technical University of Crete. His Diploma Dissertation has been awarded the First Prize in the Diploma Dissertation Contest in the area of Mechanics Science, for the period 2001-2003, organized by the Hellenic Society for Theoretical & Applied Mechanics (HSTAM). Subsequently, on February 2005 he obtained his Master of Science Diploma at Technical University of Crete. His M.Sc. Dissertation focused in the area of Fracture Mechanics. Next, on May 2013, he acquired the degree of Doctor of Philosophy in Constitutive Modeling of Rock Mechanics at the Technical University of Crete. On September 2006, he was appointed permanent staff in the Laboratory of Mine Design at the Mineral Resources Engineering Department, a position that holds up today. His main responsibilities are the supportive teaching of the four undergraduate and the two postgraduate courses provided by the Laboratory, performing Rock and Soil Mechanics experiments, supportive supervision of Diploma Dissertations and Laboratory's IT administrator. Dr Pantelis Liolios has participated in several Scientific Research Programs funded by the European Union or/and the Hellenic government. His main scientific areas of interest are *Constitutive Modeling of Geomaterials, Rock and Soil Mechanics, Fracture Mechanics, Computational Mechanics* and