

Coverage of multiaxial fatigue criteria in fatigue limit region

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Abstract

There is a power of methods aimed at calculation of equivalent fatigue limit for arbitrary multiaxial loading. Although there are so many ways of computation, their thorough mutual comparison in a larger scale is missing. The database project presented in this paper comprise of several databases crowned with the FatLim database, which comprise of a huge number of experimental results and of 18 computational method working in the category mentioned before. The great block of data was acquired using in-house fatigue software PragTic, which is offered as a freeware application. The FatLim database follows its philosophy of a simple and non-paid accessibility. Its query tool written in MySQL and PhP allows to users to evaluate a practical usability of tested methods on load cases, which the users define. All the issues covered within this paper are available on the website www.pragtic.com, structure of which is described here.

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1. Introduction

The last active presentation of the author at the Computational Mechanics conference series dates back to the year 2002. The paper concerned an important implementation step of an intern database into the PragTic fatigue solver. The next five years brought substantial development of this software.

In addition to this development, the use of PragTic allowed production of a large amount of research data. Growth of their volume brought us to a question how to save them and work with them efficiently and how to publish them without too great simplifications. The development in this category was aimed above all at the multiaxial high-cycle fatigue and is crowned with the FatLim database presented in this paper. FatLim currently sums up results of computations by 18 different calculation methods over 428 experimental points.

Both PragTic as well as FatLim are freely available on the website <http://www.pragtic.com>. The primary language used on the website is the English. The users can switch to the Czech language on pages, where the left upper corner hosts a button with the sign CZ. A complete translation to the Czech is not provided since it would took too much of my time. The program PragTic is moreover also written within English environment so some knowledge of the English language is expected. Because of the FatLim database project necessitates interaction of several databases placed on the same website and the website itself starts to growth in complexity, a description of its structure is provided in this paper so that fresh users would not get lost.

There are three domains built on the webpage: *PragTic Freeware Project*, *Database of Fatigue Limits* and *Fatigue Lounge*. They will be subsequently introduced here.

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2. PragTic Freeware Project

2.1. PragTic Programme

PragTic fatigue solver is currently released in its third public version PragTic v.0.2 (see [1] for more details). The solver is built in such a way that it enables a fatigue calculation at nodes of elements, elements, nodes to which are the results averaged and at isolated points. Isolated points are defined as an entity in order to allow a start of the calculation without any relation to some particular FE-model. As regards the input of the FE-data, PragTic offers a unique upload of a table-formatted ASCII data with only a slight dependency on their source. This method is available only for solid elements. The more convenient way of a direct import of a firmly set FE-files is currently built only for MSC.Nastran data through the import of *.nas, *.dat and *.pch files.

The implemented methods are still oriented above all to multiaxial methods of fatigue calculation. The multiaxial calculation is conditioned by an ability of PragTic to efficiently define the multiaxial load state, i.e. to relate the individual load channels. The multiaxial fatigue methods available can be sorted into two groups. The first one is concerned on a comparison towards fatigue limit. Results from these methods are the ones published in the FatLim database (sec. 4). The second group works in the region of finite lifetimes. These methods are based on Basquin and Manson-Coffin curves. The basic problem with these methods is the fact that they work with elastic-plastic strains and stresses. Such a condition leads to a requirement to process either elastic-plastic FE-results in several time instants (so-called transient analysis) or to use some approximate method to convert the elastic FE-results into the real elastic-plastic ones (as does e.g. the Neuber method in the uniaxial calculation). To avoid the necessity of a work with elastic-plastic data a PCF method based on the damage parameter of the Papuga PCr method [2] is being developed. This method is based on a description of several S-N curves. It is currently under development so any conclusions about its efficiency are very preliminary.

There are also several uniaxial strain-based methods implemented. At last, PragTic allows a start of the computation also for the LESA method (abbreviation: Local Elastic Stress Approach) in the v.0.2 release. The method is similar to that used within the FemFat[†] fatigue solver in the basic analysis. It uses the S-N curve as the basic curve but it offers coverage also of effects of stress gradient, technology or surface quality in contrast to other S-N based methods gathered in PragTic.

In the last release, PragTic got a menu item Tools where some useful utilities for a work with the FE-data can be found. These features extend the capability of a general post-processing of the FE-data within PragTic. Note that PragTic is currently built in such a way that all dependencies within the FE-model are included. An implementation of any further special method processing the FE-results or FE-topology can profit from this basis.

2.2. PragTic on Web

The program can be found under the section *PragTic SW*. To download it the user has to fill in a simple form, where he has to decide if he wants to use it anonymously (only his login name is published, nothing else) or as a privileged user. Privileged users are shown in the section *Users* in the *Fatigue Lounge* with some basic data on them published there (see sec. 3).

Except for the program itself, the *PragTic SW* section allows also download of PragTic's Help. This can be done without any registration, because it should guarantee some under-

[†] FemFat is a commercial code developed by ECS Magna Steyer. For more information see www.femfat.com.

standing of the results gathered in the FatLim database. The PragTic's Help can be also found in the same section available in a common HTML format readable by any HTML browser.

The other sections of interest are *FAQs*, where the users' questions are replied and *Bugs*, where warnings concerning bugs found in the current version are published. This part of the website should be read before any important calculation.

3. Fatigue Lounge

As written in the previous section, the users of PragTic fill in a form concerning some of their data. The same account has to be prepared by persons who would like to actively work with the data in the FatLim database. The form covers only very basic information about the users concerning their photo, age, employer and research or work activities (see an example in fig. 1). The user can hide to other users by claiming his account to be anonymous. The users who do not think that the openness could harm them and publish that data are marked as privileged users. The section *Users* in the *Fatigue Lounge* sums the information provided by the privileged users in order they would know each other. The next item in the *Fatigue Lounge* is the *User Profile* section, where the users can change the information saved within their accounts.


Username: papuga	Jan Papuga	
	Born:	1975
	Lives in:	Kunovice, Czech Republic
	Working at:	Evektor & Czech Technical University in Prague
	Current fatigue topics:	multiaxial fatigue
	Further focus:	creep & fatigue interaction, random loading
Message:	If you have any original papers referring to fatigue limits under multiaxial high-cycle load conditions, please, could you tell me and potentially send me a scan or copy? I would like to create an accessible database of results of different computational methods. Currently I am more specifically interested in notched specimens or loading in different frequencies. But every original is welcomed - there are so many reproduction errors everywhere.	

Fig. 1. If you want to become a privileged user, do not worry about necessity to publish any very personal data. The items published can be seen in this cutout.

The section *Forum* enables to users to write on ideas and problems they encounter during their work or research. The forum is accessible by privileged users only.

The item *Bulletin* provides actual news concerning PragTic development, fatigue calculations, important changes on *www.pragtic.com*, conferences, which I plan to attend, or publications, which I prepare. I hope in some close future I will be able to built a next database of actualities, which would be able to print them out to the Bulletin and to e-mail them to users who subscribe to an e-mail list.

The item *Conferences* is an interface to a database containing data on conferences with fatigue, FE-analysis or structural mechanics topics. The database enables to write a conference record to any logged user (no matter if anonymous or privileged one). The concept of a data manager described later in the sec. 4.1 is valid here as well. The logged users can mark conferences, which they expect to attend so that the others would know they could meet there.

The section *Reports* currently consists only of my PhD thesis, which can be downloaded there as well as one paper from the Fatigue and Fracture Mechanics '2006 conference. The section *Links* gathers some interesting links to fatigue-oriented topics. The section *Sponsors*

publishes the organizations and companies, which provided finances for the development of either PragTic or the database set around the FatLim database.

4. Database of Fatigue Limits

The FatLim database today relates to experiments resulting in either uniaxial or multiaxial fatigue limits obtained under harmonic or static loading on individual load channels. There is an expectation that the experiments were done with smooth unnotched specimens.

The FatLim database is in fact a set of databases related together, where the database of Fatigue Limits is the top end, built over the data gathered in databases of references, materials, groups of experiments, parameters of individual experiments and results of different computational methods.

The first idea to built such a database cross my mind, when I decided to test my new criterion Papuga PCr [2] for a multiaxial fatigue limit detection. I built a set of experiments from data, which I found in scientific papers of other authors. When I continued and my private MS Excel aggregate of data started to grow in volume I met two problems. First, the Excel file started to collapse nearby 5MB size. Second, I started to doubt over the data. Many of them were contradictory or in some way confused. I decided to go back to the primary sources of the data and if possible to abandon the secondary sources. Now I estimate that an indispensable part of data referenced in the scientific papers is in some way wrong. The subsection 4.1 will explain how I hope the data saved to the database can be secured from erroneous inputs. I believe the chosen way of the data publication is the only possibility how to get back to the correct primary data and to guarantee to other researchers that they are right and can be used.

The most of the databases here are accessible by privileged users. In order to ensure that only relevant data with the lowest possible occurrence of errors will be given to the database a system of Manager, Sign, Edit and Revision was developed and is subsequently introduced to the databases.

4.1. Manager, Sign, Edit and Revisions

When a registered user decides to add some data to the databases, he has to understand that he accepts a manager post as concerns that added data. His username used within the *www.pragtic.com* is appended to the added item and the rest of users thus know who is responsible for its appearance in the database. The manager is the only person (except for the administrator of the database) who can directly change anything in the created item.

If any other user wishes to add any new information to some existing data controlled by another manager, he has to accept another way of edition. He edits the item, but the old item is not rewritten after the last confirmation. A new item described as a revision is created in the database. The manager of the data is notified about the revision and has a time limit of 30 days within which he has to either accept or reject it. When the revision is accepted it replaces the original item. If it is rejected, the originator of the revision still can publish his case in the *Forum* and call for a justice. In the case the manager does not do anything within the time limit, it is expected that he is not active or interested any more. The managerial authority to the item is assigned to the originator of the revision and the revision replaces the original.

The users can back up a validity of any data set by signing it. Their username then appears if the item is printed out. The users can sign even the revisions in order to notify their personally performed comparison to the primary source giving the same result as being actually presented to all other users.

The system of revisions is not fully implemented anywhere within the site. I hope I will be able to finish it before the end of the year 2007.

4.2. References

The description of any fatigue experiments or material variables depends on provision of the appropriate reference to the report, where the data can be found. If it is possible, the report should be a primary reference, not related to any previous publication of the data. As I found during my research, the use of secondary sources too often leads to an inclusion of many errors cumulating during any previous transcription.

The section References offers an interface allowing to find the appropriate reference you are looking for, to add a new reference or to edit it. An important point for you if you wish to add a new reference to a paper in some proceedings is that the record for the proceedings themselves has to be prepared. The concept of *Signing* is not planned to be active for the references since their form is not so important.

4.3. Material DB

The database of the materials was the first one, which I designed – thus the interface to it is slightly other than in the case of other ones. The user is invited to choose one material from the list on the title page. If more items are chosen, only the last one is printed. If there are more records for the material chosen then buttons with marks "<" and ">" can be used for their listing. The use (and appearance) of buttons *Edit* and *Add New* is reserved to logged users.

Each record of a material contains its mark, an alternate mark, a number of material variables, its chemical composition, references to papers read from the *References* database and a commentary for the data which could not get into the other edit fields. The number of references related to one material record is three. It is expected that they all relate to the same material batch.

The basic idea of the material database consists in my opinion that there are many material variables relatively completely recorded in research and scientific papers. They are nevertheless crumbled up to many papers. The farsighted researchers have already built their own databases, but the younger ones as e.g. PhD students are lost in such a situation and do not know where to look. An accurate citation within the database with a full reference to all papers used should enable such users to at least start. The reference to the original paper should secure the citation from any breach of the law.

The *signing* concept is very necessary here. The signs of more users should ensure to the user that he could rely on the variables as well as on the reference. The database is very young and I appeal to all readers of this paper to join in my effort and sign or discuss the topics in the database.

4.4. FatLim Database System

As stated before, the FatLim database is the top end of the database system data of which can be found in the section *Database of Fatigue Limits* and *Fatigue Lounge*. It uses access to the databases built on references, materials and users. The data covered within FatLim are separated to groups of experiments, for each of them is provided description of load conditions and of fatigue results provided by those 18 calculation methods.

This database still has not fully equipped interface for adding of new items. The concept of signing (or sign removing) has been already implemented and also the editing is enabled to managers of the data.

The data record is based on the definition of the test group with a unique mark, which all the tests within the group will start with. The test group is related to one reference and one material from appropriate databases. It also points to another database where the experimental

conditions are saved. The set of test group and the load conditions is expected to have one common manager and can be as well as signed as a whole.

Each computational method has a reserved space for results obtained from calculation with the method on the test group data. Each calculation method in each test group has one manager and can be signed as one unit. There are several options to add to the numerical result of prediction provided on a test item:

- not computed
- analytical solution
- PragTic
- no solution

As regards an edition of any existing item, the user has to be a manager of it and has to be logged in. To start the edition when you are logged in, please, choose the appropriate test group in the FatLim Selector on the FatLim DB title page. Then push the button Show Group. In comparison to a non-logged user the card of the test group provided on the new page will host small green buttons with “E” and “S” or “RS” signs. The first group of them appears on the top near the name of the test group to which it is related. The rest of them can be found in the line of individual calculation methods. The “E” sign is for “*edit*”, “S” for “*sign*” and “RS” for “*remove sign*”. You can see on this card if the load data or the results are already signed by anybody or not.

4.5. Comparison Methods Used in FatLim

Nearly any common calculation method oriented on evaluation of the loading towards the fatigue limit can be rewritten to a general formula:

$$D_p = function(C_a, C_m, N_a, N_m) < f_{-1}, \quad (1)$$

where the damage parameter D_p is a function of shear C and normal N stresses on some particular plane or more planes. The indices a and m are there for amplitude and mean value. The variable f_{-1} stands for fully reversed axial fatigue limit – either the bending or tension one in dependency to the axial loading of the examined experiments. The inequality in (1) says that the cases where the damage parameter is less than the fatigue limit, mark loading which should fall into the region of infinite fatigue life lying behind the fatigue limit.

In FatLim, we are thoroughly testing validity of the multiaxial criteria on experiments prepared for definition of fatigue limits under multiaxial load conditions. The inequality in (1) should become the equality for such data. Unfortunately, something like this happens only rarely. We have to define the deviation from the equality much more often. Since the right hand side of the (1) has a meaning of the fatigue limit, the fatigue index error defined as:

$$\Delta FI = \left(\frac{D_p - f_{-1}}{f_{-1}} \right) \cdot 100\% \quad (2)$$

could be understood as a relative deviation from the ideally set fatigue limit. The positive sign of the fatigue index error means that the specimen would be already broken in such a case – the result is conservative. Negative ΔFI values correspond to a non-conservative prediction.

The FatLim database joins together large number of experiments and even much higher number of computational results. The only way how to not get deadlocked in comparisons of so many individual results, the statistical approach has to be used. The statistics provided by the FatLim covers the maximums, minimums, mean values, ranges (max-min) and standard deviations (see tab. 1). The quality of any calculation methods is evaluated by a synergic assessment of the mean value, range and standard deviation.

The computational methods themselves are so many that it has not much sense to publish them here. Their description can be easily found in the PragTic's Help (sec. 2, see the same reference in fig. 2 on the bottom).

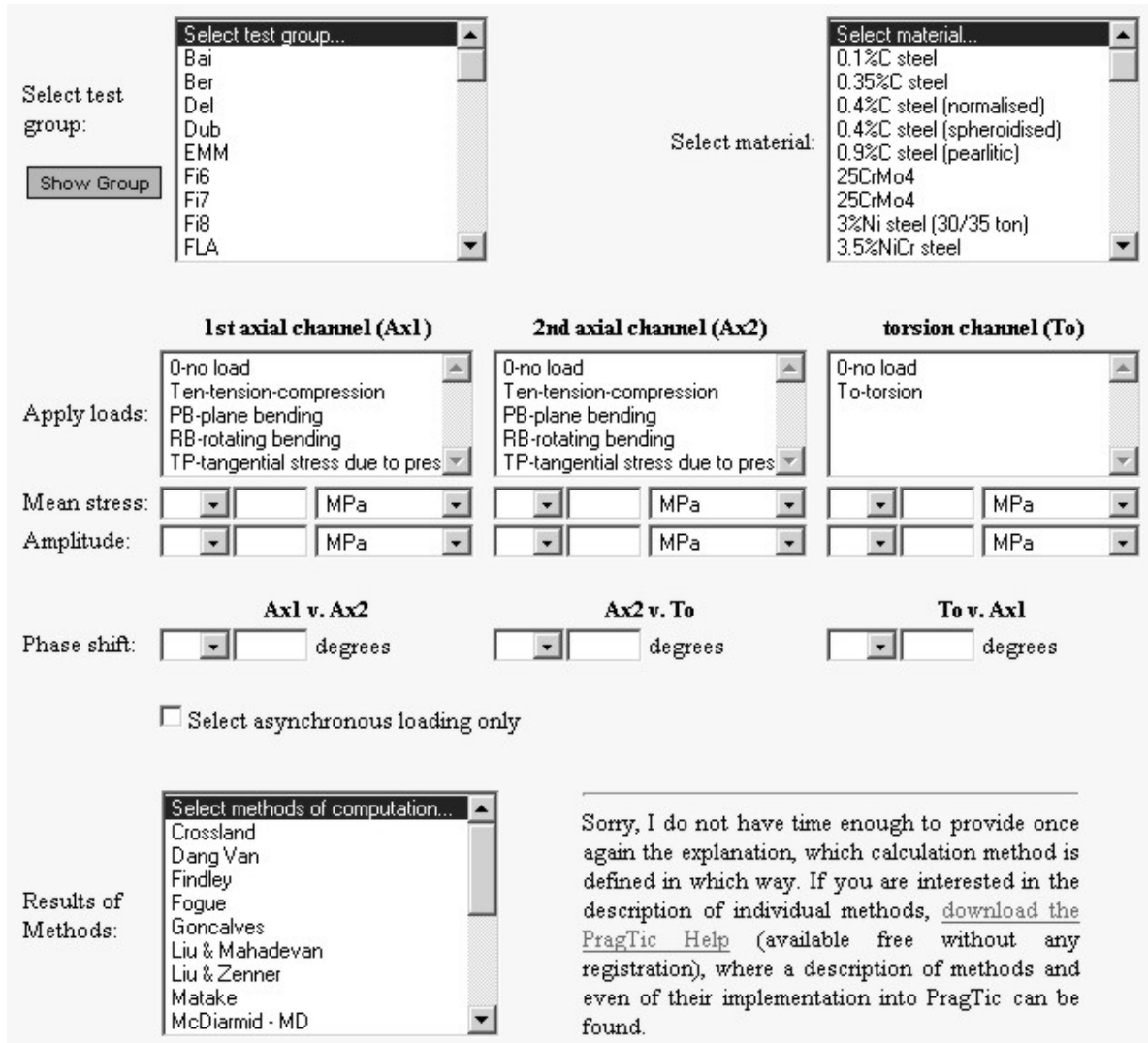


Fig. 2. FatLim Selector enabling to print out only desired type of data.

4.6. FatLim Selector

The FatLim selector started by the *FatLim DB* button is there to enable to filter the data that the user wishes to compare (see the cut out from the website in fig. 2). It allows to print-out only some test groups, tests on particular materials, tests with some predefined range of stress amplitude or mean stress, tests with a defined load combinations and so on. The user can also choose, results of which calculation methods he wants to see.

If any calculation method is selected for the printout, the printout is accompanied by a prepared statistics over the chosen tests. The statistic variables are the same as shown in tab. 1.

	Sines	Crossland	Findley	Dang Van	Matake	McDiarmid - MSSR	McDiarmid - MD	Papadopoulos	Liu & Zenner	Robert	Fogue	Spagnoli v. SWT	Spagnoli - v. MD & SWT	Goncalves	Papuga PI	Papuga PCr	Liu & Mahadevan	Ninic
Number of real results	421	421	428	428	428	428	428	428	428	428	407	231	428	418	428	428	428	308
Number of N_C results	7	7	0	0	0	0	0	0	0	0	0	197	0	10	0	0	0	120
Number of N_A results	0	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	0
Mean value	-7	-8	8	-1	6	-8	-6	-4	-1	4	1	-1	4	1	1	-1	-1	1
Maximum	48	17	83	45	84	21	22	28	35	39	55	27	62	50	38	18	47	58
Minimum	-82	-77	-18	-77	-50	-52	-45	-77	-64	-32	-39	-40	-40	-39	-27	-20	-51	-22
Range	130	94	101	122	134	73	68	105	100	71	93	67	102	89	66	38	98	80
Standard deviation	17	12	15	13	16	12	12	11	9	9	10	9	11	11	9	6	12	9

Tab. 1. Statistical evaluation of all currently saved data gathered in FatLim. The N_C sign relates to tests for which the results for the particular method were not computed, N_A cases, where the results were not available (the material properties were out of a definition limit).

5. Conclusion

Both FatLim and PragTic are created as research tools, which can found their use even among engineers in common technical practice. Any user can verify results saved in FatLim by a computation in PragTic, but the database system is the most efficient tool, how to help the users from infinite repetition of such tests.

The advantage of FatLim lies in the fast availability of required data. When some engineer or researcher has to solve the problem, which fatigue criterion would be the best to be used, if the load conditions at the critical place have some definite form, than FatLim can respond very quickly. Unfortunately, the most of the commercial fatigue postprocessors implement only methods by Findley or Dang Van, scoring of which is not very fine (tab. 1).

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