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INTEGRATION OF DAMAGE DIFFERENTIALS (IDD) FOR FATIGUE LIFE ASSESSMENT UNDER ANY LOADING

AUTHOR’S SUMMARY

OF

THESIS

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FOREWORD

The phenomenon of **fatigue of materials** due to variability of loading was realized in 19th century. Most of the fractures of engineering structures are due to fatigue and the consequences are disastrous. How to envisage in what operational lifetime fatigue failure would occur, i.e. how to assess the fatigue life, has been one of the most important engineering problems for the last two centuries. *There was not any uniform and all-acknowledged solution under any loading including the general multiaxial case of non-proportional, non-cyclic and arbitrary wave-forms of the stress components.* According to the thesis, the lack of solution was since the fatigue life had not been searched by means of an integral of fatigue damage differentials. Such a possibility had not been revealed and exploited before but it can be practically implemented nowadays thanks to the computers.

The thesis opens a **new scientific research line** under the IDD abbreviation. The underlying statement is that only the universal mathematical way of the calculus from differentials to an integral can establish a uniform and all-acknowledged solution to the problem of fatigue life evaluation under any loading. *The new line proposed would re-direct a vast world-wide research experience, accumulated for nearly two centuries, into another course. The basic notion of that experience is loading cycle and therefore the hitherto existing approach is called Cycle Counting Approach (CCA). In the thesis, another, new and radically different IDD approach is proposed: the basic, general notion is loading differential, while loading cycle remains as a particular notion, and the damage differentials per the separate loading differentials are integrated (summed).* That such differentials are introduced for fatigue life assessment may have the same importance which the differentials introduced in the mathematics and exact sciences generally have: decisive.

The development of the IDD approach and creating unique IDD software has been done by the author only what has inevitably engaged a lot of time: about 30 years. Since everything proposed here is entirely original and without any existing analog, the colleagues in the world and in Bulgaria have taken an explainable position of waiting for results. Thus, the IDD work continued most of the time without any collaborators, nor any financial or other support. Nevertheless, the IDD approach has become well-known and discussed in the world.

What is said above, as well as the necessity of juxtaposition to the nearly two-century CCA experience, explain the inevitable fact of a comparatively large volume of the thesis: 353 pages (with expanded line spacing and with an IDD-software manual included). But the colleagues that will study it, as well as the members of the scientific jury, will quickly orientate themselves to the main points. To help them, this Summary, this Foreword and an extended peculiar Preview serve. Then, the Conclusion and the Contributions (presented separately) can be read. Afterwards, the details can be entered: the new notions, the mathematical instruments, the software created for practical application of author's IDD method, the verifications carried out and their results, and so on. The volume of these details has been compressed to an acceptable minimum. The IDD site cited above has been organized in a way as to also facilitate the study of the thesis. Besides, the site gives the IDD software as freeware. As well, the site gives the files involved in the sections of the thesis and in the verifications.

Eventually, this foreword hints that the thesis is expected to evoke great interest and opinions under considerable scientific responsibility on the part of the scientific jury members and the other colleagues. To all of them the author renders homage and his expectation of a just evaluation.

CONTENTS

(In the parentheses at the right margin, the page numbers of the thesis are put. Some of the contents items of the thesis are not included in this summary.)

5.9. Conclusions from Chapter 5

5.9.1. IDD N_{cmp}-N_{exp} diagram

In Fig. 5.9.1-1, there are placed in all 49 values of N_{exp} and corresponding 49 values of N_{cmp} from the adaptation (0) and the verifications (1) – (6). Thus, Fig. 5.9.1-1 presents the IDD N_{cmp}-N_{exp} diagram as a conclusion from Chapter 5. Three of the N_{exp} values are considered as 'greater than' for the availability of run-outs (survived specimens). For the rest

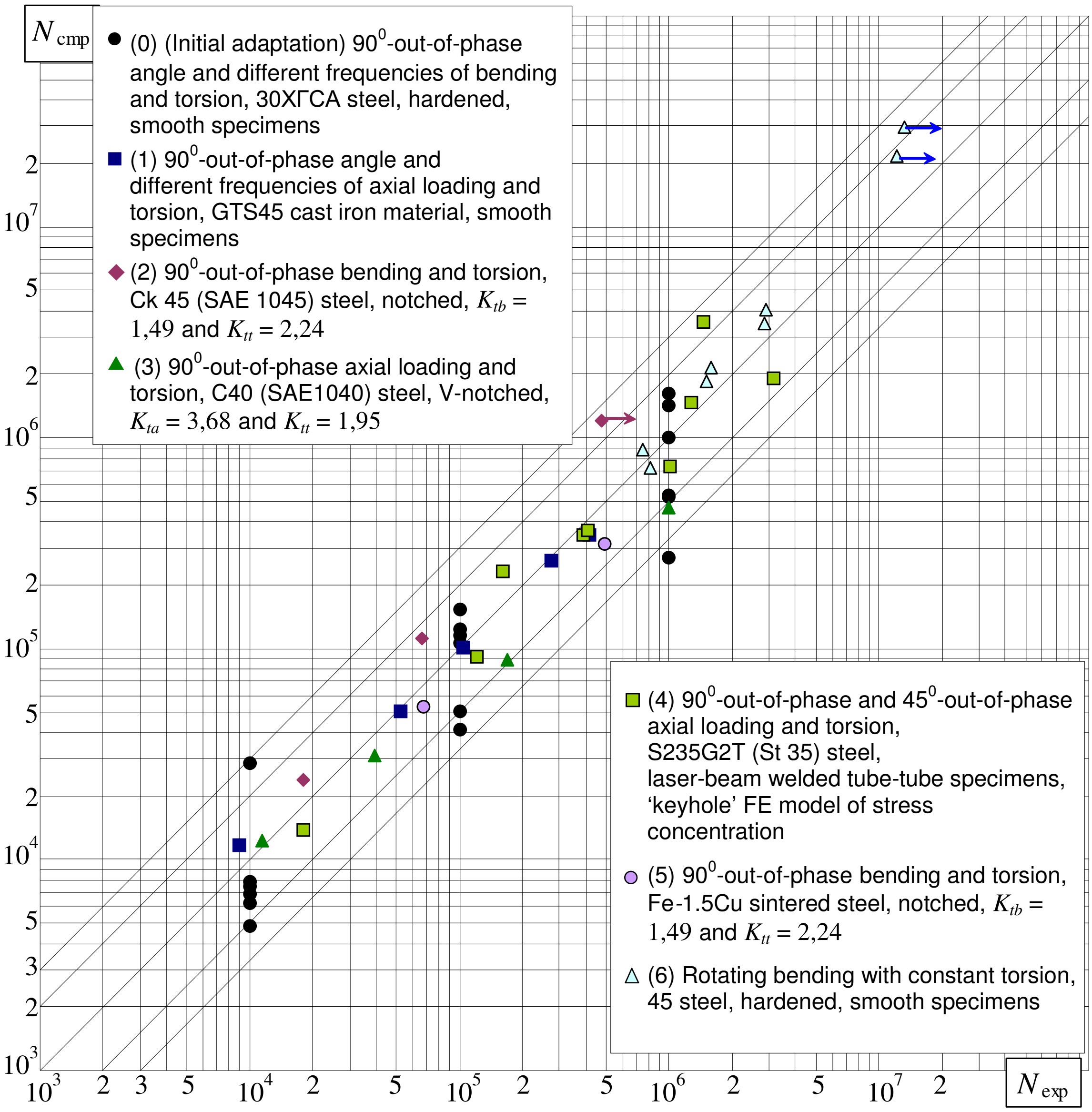

Fig. **5.9.1-1**. IDD N_{cmp}-N_{exp} diagram from the (0) initial adaptation and the (1) – (6) verifications (the $N_{\text{cmp}}/N_{\text{exp}}$ ratios have 1,02 average and 0,52 standard deviation from the average)

46 $N_{\text{cmp}}/N_{\text{exp}}$ ratios the statistical data (Ch5.xls file) are valid, as follow.

The average is 1,02: an extremely good result. The standard deviation (from the 1,02 average) is 0,52: a very successful result. It means that in future similar IDD applications N_{cmp} will be expected to appear most probably between $1{,}54^{-1}N_{\text{exp}} = 0{,}65N_{\text{exp}}$ and $1{,}54N_{\text{exp}}$. The greatest deviations of $N_{\text{cmp}}/N_{\text{exp}}$ are Min $0{,}27 = 3{,}68^{-1}$ and Max 2,86. They have both appeared in the initial adaptation whereas in the verifications (1) – (6) Min is $0{,}47 = 2{,}14^{-1}$ and Max is 2,45. By the way, the average of $N_{\text{cmp}}/N_{\text{exp}}$ from the verifications (1) – (6) is 1,05 and the standard deviation is 0,41.

5.9.2. Empirical data bank of the IDD parameters and conclusions

So far, based on the thesis (and the latest studies being placed in Volume II), the following empirical data bank (Table 5.9.2-1) has been formed for the first practical category of non-proportional loadings. The bank is, of course, initial and uncompleted but is a good basis for next IDD fatigue life evaluations.

<table>
<tr><td colspan="5">Table. **5.9.2-1**. Empirical data bank of the IDD parameters for the first practical category of non-proportional loadings</td></tr>
<tr><td colspan="2" rowspan="2">IDD parameters</td><td colspan="3">Confirmed for</td></tr>
<tr><td>R_m, $R_{p0,2}$ MPa/ Materials</td><td>Specimens</td><td>Loadings</td></tr>
<tr><td rowspan="3">Steels</td><td>$f_c = 2$
$f_\tau = 3$
$N_c \geq N_r$
$N_\tau \geq N_r$</td><td>1490, 1300/ 45 (hardened)
1310, 1090/ 30ХГСА
1030 (welding), 350/ S235G2T (St 35)
850, 704/ Ck 45 (SAE 1045)
715, 537/ C40 (SAE 1040)</td><td>Smooth and notched (with K_t to about 3,68), and welded</td><td rowspan="4">Non-proportional bending or axial loading and torsion with t_c to about 0,62 and t_τ to about 0,73, with $\sigma_{equ,m} = 0$ and $\sigma_{equ,m} > 0$, with various forms of trajectories</td></tr>
<tr><td>($2 > f_c > 1$,
$3 > f_\tau > 1$,
$N_c > N_r$,
$N_\tau > N_r$)</td><td>(551, 365/ 11523.1)</td><td>(Smooth)</td></tr>
<tr><td>$f_c = 1$
$f_\tau = 1$
$N_c > N_r$
$N_\tau > N_r$</td><td>410, 300/ Fe-1.5%Cu</td><td>Notched</td></tr>
<tr><td>Cast iron</td><td>$f_c = 2$
$f_\tau = 3$
$N_c > N_r$
$N_\tau > N_r$</td><td>449, 305/ GTS 45</td><td>Smooth</td></tr>
</table>

According to the previous Section 5.9.1 and speaking more generally, the expected inaccuracy of N_{cmp} would be less than 2 as an error factor (i.e. $0,5 < N_{cmp}/N_{exp} < 2$). This inaccuracy can always be directed to the safety side by setting proper higher values of the four IDD parameters.

Next verifications intended will precise Table 5.9.2-1 and would change its structure. So far, it seems that f_c and f_τ for steels are in correlation with the static strength: f_c and f_τ are 2 and 3 in case R_m exceeds ≈700 MPa, and f_c and f_τ decrease to 1 and 1 when R_m is down to about 410 MPa. It is expected that the correlation considered will be expressed later as clearer functions $f_c = f_c(R_m)$ and $f_\tau = f_\tau(R_m)$ in intervals with lower limits about 1 and upper limits about 2 and 3. These intervals are not large and therefore even a significant scatter of the functions $f_c(R_m)$ and $f_\tau(R_m)$ in them would not deprive every new fatigue life assessment of success. So far, the data in the Specimens and Loadings columns of Table 5.9.2-1 do not seem to influence $f_c(R_m)$ and $f_\tau(R_m)$. In other words, f_c and f_τ seem to be valid for any specimens and any loadings of the first practical category, as well as for non-zero static levels of the oscillograms.

The cast iron material in Table 5.9.2-1 has shown $f_c = 2$ and $f_\tau = 3$. It will be interesting and important, of course, to have data for f_c and f_τ obtained also for aluminum alloys and other materials.

The studies on the 11523.1 steel, included in the data bank, relate to smooth tubular specimens subjected to non-proportional tension-compression and torsion. These studies continue after the presented final version of the thesis and go into the Volume II. They are done together with Jan Papuga and other Czech researchers. Publication of the results is envisaged for later (therefore, parentheses are used in the corresponding row of Table 5.9.2-1). Variant trajectories with various interesting forms in the σ_x-τ_{xy} plane were implemented. Computed IDD lives are obtained in a good agreement with the experimental ones in case f_c and f_τ are set by interpolation to be between the values valid for C40 (SAE 1040) and Fe-1.5%Cu. This confirms the above-mentioned decrease in f_c and f_τ due to a decrease in R_m.

Dr. Papuga has also applied other methods but so far their computed lives results significantly yield to the IDD results.

The numbers N_c and N_τ are left with some indefiniteness in Table 5.9.2-1. In fact, the areas L_c and L_τ are not strictly given. This corresponds to the opinion, already mentioned, that the notion of fatigue limit contains some uncertainty and fictitiousness especially under arbitrary non-proportional loadings. What only looks for sure is that the L_c and L_τ lines should be more inward to the coordinate origin than the L_r (or L_l) line. This can be ensured even by the equalities $N_c = N_\tau = N_r$ but only if $f_c > 1$ and $f_\tau > 1$. Otherwise, in case f_c and f_τ near 1, then $N_c > N_r$ and $N_\tau > N_r$ should be set.

As to trajectories which go farther out of the L_r area, setting N_c and N_τ to be or not to be greater than N_r does not seriously influence N_{cmp}. However, if the trajectory does not go out of the L_r area, then the selection of N_c and N_τ to be greater than N_r becomes important. As already discussed, if a trial increase of N_c and N_τ sharply changes N_{cmp}, then stronger inequalities $N_c > N_r$ and $N_\tau > N_r$ should be preferred. Generally speaking, as a tentative recommendation, N_c and N_τ should be selected in the order of $10N_r$ with possible error in favour of safety.

It is to additionally note that fatigue life assessment methods are also proposed by a part of the authors of the experimental data used in the IDD verifications done. None of those methods has been simultaneously applied to all the experimental data of the six IDD verifications. If such a trial is done, it will be seen that the conclusions from the review of the existing methods (Section 1.5) are confirmed: too various methods, proved only in specific lading cases, incompatible (or inapplicable) and conflicting to each other in all the cases.

CONCLUSION
(Concluding notes)

The mechanism of forming the fatigue life is too complicated and inscrutable. This provides a possibility to every researcher to propose his own CCA method (model) for fatigue life assessment which contains some partial truth and is experimentally confirmed in some limited scope. Another researcher, under different experimental data and different loadings, does not find confirmation of the previous method and, in his turn, also proposes his own model. After all, there is not any uniform, all-acknowledged and universal CCA method but there are many disputable methods comparing to each other, each one with its partial truth and that is why they tolerate each other.

Now, something radically different is proposed: not to have loading cycle as the basic notion but to have it as a particular notion, and, instead of searching for disputable cycles, to follow the indisputable differentials (Fig. 1.1-3b) of any loading and directly compute the damage differentials per the loading differentials.

Thus, it is not simply about a serial new method in expectation of a tolerant attitude. Now, a united skeptical or negative reaction is possible: considering that many thousands of fatigue life researchers in the world had searched for cycles in every loading, the IDD concept and the author's IDD method could make a lot of opponents. They could even state that IDD rejects all the accumulated fatigue life knowledge built on the basis of the notion of loading cycle. On this occasion it is to pay attention again to the contributions 2.3 and 13.4: IDD rejects nothing of the existing knowledge. The thesis has entirely been built on the basis of the existing knowledge and the main idea is to use it in another way.

It is understandable that the colleagues would express skepticism and jealousy after they have devoted theirs investigations and careers to CCA and received acknowledgements and degrees for that. It is understandable that they would look for weak points of the IDD concept and of the author's IDD method, and would raise controversial questions since the complicated and inscrutable mechanism of forming the fatigue life leaves a large place for a lot of disputation.

However, there is a possibility which leaves no place for disputation on whether IDD should be acknowledged or not, as follows.

Let any IDD opponent verify any other fatigue life evaluation method by using the same experimental data files used also by the author in the IDD verifications done in Chapter 5. Let the verification in Chapter 3 be also added. Let the verification or verifications continuing in Volume II be added, as well. All the experimental data are not of the IDD author but of other authors and therefore a partial selection of one's own experimental data is excluded. And if the IDD opponent proves that the other method is always applicable in all the mentioned cases and categorically excels the IDD method, then the disputation ends: the IDD method should withdraw. Moreover, the other method will prove to be that missed one which can claim for general validity now. But if the other method yields, the disputation ends again: the IDD method should be given the right of way. Moreover, resetting and canalizing the world investigations to IDD should be recommended.

If the other method and the IDD method turn out to be approximately tantamount, again the IDD method should be given the right of way to continue comparing and proving itself in next and next verification (Volume II). With that, the oscillograms should purposefully be diversified as much as possible: to be of both the first and second practical category of non-proportional loadings, and of mixed loading with various trajectory ratios t_r, t_c and t_τ, and of various trajectory's forms, and of both cyclic and non-cyclic loadings, and of both deterministic and random loadings, and of pure r-loadings, pure c-loadings, pure $\mathrm{d}\tau$-loadings, and so on.

Hereby the author closes and lets the colleagues and the honorable scientific jury members take the scientific responsibility for the evaluation of the thesis.