FATIGUE OF STEEL STRUCTURES

P. BROŽ

Klokner Institute, Czech Technical University,
Šolínova 7, 166 08 Prague 6, Czech Republic

The objective of the paper is to report about the main results and conclusions of a new stage of experimental research conducted in Prague on the coupled problem of a many times repeated loss of stability and cumulative damage in the slender webs of steel plate girders subjected to many times repeated loading. In so doing, the paper analyses the experimental data obtained, particularly from the point of view of the initiation and propagation of fatigue cracks in breathing webs, their failure mechanism and relation to the fatigue limit state of the whole girder.
Some comments concerning the issues of metal fatigue are added.

1. Introduction

Steel bridges, crane runway girders and similar systems are exposed to many times repeated loading and, if their webs are slender, they repeatedly buckle out of their plane. This phenomenon is now usually termed "web breathing" (see eg [1]), and generates pronounced cumulative damage in the webs, so that fatigue cracks usually occur in them. No reliable design procedure for the webs can then be established without the regime of crack initiation and growth in them having been thoroughly mapped.

2. Fatigue damage in thin-walled steel girders

The webs of the plate and box girders of steel bridges and like structures are subject to many times repeated loading; consequently, being usually slender, they exhibit many times repeated buckling, this process being now named web breathing. In is in the nature of this phenomenon that considerable cumulative fatigue damage is then generated in the girders, this very substantially affecting the limit state of the girders.
Designers of steel structures have for some time been aware of the importance of the breathing process and have been trying hard to incorporate it into design. Two simple approaches have been used to reach this objective:
(i) In the first of them, the depth - to – thickness ratio of the web is reduced so that all uncalled-for effects of web breathing may be neglected.
(ii) In the other, it is the load acting on the web that is reduced to achieve the some objective.
Both of the two aforementioned procedures are useful, but they hold out just part of the solution needed. They represent only a lower bound for this solution; a more economical approach, such as to go beyond this lower bound and to be profitable at least from part of the post-buckled reserve of strength of slender webs, is also very advisable.
With the importance of this approach to the breathing phenomenon for reliable and economical design of steel bridges and similar structures, extensive research, both theoretical and experimental, was started in Prague, several years ago, at both the Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences and Klokner Institute.
In the theoretical field, three studies are running or have already been closed:

(i) A large deflection theory analysis of stresses in crack – prone areas of breathing webs.
(ii) An analysis, based on Fracture Mechanics, of the propagation of cracks in breathing webs.
(iii) An ultimate load theory for fatigue – cracked webs subjected to predominantly shear.

The experimental investigation consists of several series of tests on steel plate girders under the action of many times repeated load, the geometrical characteristics of the test girders and the regime of the cyclic load being varied in them.

Two series of test girders were tested, by M. Zornerová and M. Škaloud, at the Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences in Prague.

(i) One series of girders with slender webs, whose depth–to-thickness ratio $\lambda = 250$.
(ii) Another series of girders with less slender webs, whose depth–to-thickness ratio $\lambda = 175$. This depth–to-thickness ratio was chosen so as to be lower than the maximum slenderness $\lambda^{n,b}_{max}$ of so-called non-breathing webs discussed above.

The former group to date comprised 71 test girders, the latter 22 girders, but experiments of other girders in both groups are running.

As it was demonstrated during static tests on the ultimate load behaviour of shear girders that these characteristics were fundamentally influenced by the flexural rigidity of girder flanges, one half of the test girders were equipped with very flexible flanges (50 x 5 mm) while the other half had more rigid flanges (50 x 10 mm).

Two other series of girders were tested at Klokner Institute of the Czech Technical University in Prague. In the first one, the web thickness $t_w = 4\ mm$ so that the web depth–to-thickness ratio $\lambda = 200$ (this means, that these girders were designed so as to have as good as non-breathing webs); in the other, $t_w = 2,5\ mm$ and $\lambda = 320$. Like the girders tested in the laboratory of the Institute of Theoretical and Applied Mechanics, even the above girders had two kinds of flanges being thin ($t_f = 8\ mm$) and for the others being thicker ($t_f = 20\ mm$).

The former series comprised 12 girders and is regarded as completed; the latter to date consisted of 13 girders, but other experiments are under way.

So, if looking at the general details of all the girders tested, it can be seen that the depth–to-thickness ratios of their web panels (which is beyond any doubt one of the main factors affecting web breathing) were of 175, 200, 250 and 320. Accordingly, they ranged from so-called non-breathing webs to very slender ones.

All the test girders were subjected to a point load $F = 2\ P$, located at mid-span and cycling between a minimum value $F_{min} = 10\ kN$ and a maximum value F_{max}, which varied from test to test. Both of the two web panels were then exposed to combined shear and bending, with the influence of shear predominating.

In addition to usual deflection and strain measurements, the main objective of the experiments was to study the initiation and propagation of cracks in the webs and the fatigue failure mechanism of the test girders. This was achieved largely by way of visual inspection checks of the breathing webs, aided by a magnifying glass. In several tests the acoustic emission method was also applied.

The strain measurements were used mainly to determine the zones of stress concentration in the crack-prone areas of the breathing webs, this being also supported by a theoretical study based on the finite element method.

Before every test, the initial curvatures of both web panels were cautiously gauged, and so was the plastic residue (including fatigue crack) in the web sheet and girder flanges after the termination of the experiment, this rendering it possible to study the collapse mechanism of the test girder.

As stated above, the main intendment of the experimental investigation was to study the initiation and propagation of fatigue cracks in the breathing webs, and their impact on the failure mechanism of the test girders.

It was seen that the fatigue cracks arose at the toes of the fillet welds connecting the web sheet panels with their boundary members (ie flanges and stiffeners). They initiated at the regions of maximum principal surface stress ranges and grew, with the number of load cycles increasing, along the boundary members and often diagonally across the corner of the web as well, so as in the end to “cut” the tension diagonal in the buckling web sheet.

The initiation and the character of crack propagation was as follows:

(i) Either a crack appeared in the diagonal tension band and rapidly advanced in a direction approximately perpendicular to that of the tension band. But still, this situation occurred only twice among the almost one hundred and twenty tests performed in Prague to date, and was probably owing to the presence of a manufacturing imperfection in the web material at the zone of crack initiation

(ii) Or a crack started close to the inner or outer transverse stiffener, namely near that portion of the stiffener into which the diagonal tension band in the web anchored, then propagated and rather at a slow pace – along this stiffener. Later on, as a rule, after several tens or hundreds of thousands of loading cycles (this depending on the magnitude of loading), the crack turned inside the web sheet.
(iii) Or a crack initiated in the close vicinity of the fillet weld connecting the upper flange with the web sheet, then propagated (at first in both directions) along the weld so that on one side it reached the adjacent web corner. Then it turned down along the vertical fillet weld joining the web sheet with the final stiffener, so that in the close the whole upper outer web corner tore away from the web peripheral frame. It was observed that the tearing off of the web sheet occurred in that portion of the web in which the diagonal tension bend developed and was anchored into the boundary frame.
(iv) In some cases, phenomenon (iii) interacted with process (ii), ie with a crack advancing (with a certain delay as far as the first crack) along the transverse stiffener.

An examination of strain gauge measurements indicated that the cracks initiated in those regions (near the transverse stiffeners or the upper flange) where the ranges of the principal surface stresses in the web sheet were maximum.

The number of load cycles to failure, ie the life of the test girder, was a function of load range, and varied from tens of thousands of load cycles when the load diapason was large to millions of load cycles when the load range was small.

The propagation of the fatigue cracks was a more or less continuous process. Never during the tests did we notice any sudden increase in the rate of crack propagation, such as to indicate an unstable crack growth and to announce a critical length phenomenon known from Fracture Mechanics.

The collapse of the girders was presented in a typical shear failure mode, well marked plastic buckles constituting along the tension diagonal of the web panels and plastic hinges developing in the flanges. In the end Stage of their fatigue lives, all the test girders conducted themselves like ones with an opening in their webs, the opening being represented by the developed fatigue crack.

The effect of web slenderness was studied by way of one series of experiments performed at the Institute of Theoretical and Applied Mechanics in Prague, namely via tests on girders of group (ii), described above, the main aim being to check whether there existed a maximum slenderness $\lambda^{n,b}{}_{max}$ such that for $\lambda \leq \lambda^{n,b}{}_{max}$ all effects of web breathing could be neglected.

In this regard it was found out that the problem was more complex and that it was impossible to define $\lambda^{n,b}{}_{max}$ independently of other factors, principally of the intensity of repeated loading and the magnitude of the initial imperfections of web panels.

The main conclusions of the experiments are dual:
(A) The webs of all the girders being part of this group (ii) exhibited pronounced breathing.
(B) Referring to the initiation and growth of fatigue cracks in them, it was observed that just in part of the experiments no cracks in the breathing webs were discovered. On the other hand, it was concluded that when (a) the maximum value F_{max} of the cycling load F was high and (b) the initial curvatures of the breathings webs were not small, the mechanism of fatigue crack growth was very like to that which was observed in the tests on group (i) test girders with web slenderness of 250.

It is normal practice in the fatigue analysis of civil engineering steel structures that this analysis is based on stress range only, the effect of the mean value of cyclic stress being completely disregarded. This is why ones of us wanted to verify whether this idea could also be applied for the fatigue assessment of breathing webs.

18 tests of this kind have hitherto been carried out at the Institute of Theoretical and Applied Mechanics.

Although the scatter of the results obtained was rather large (but this is the case with all web breathing tests), it was rendered that at least in some of the experiments, the influence of the mean value was quite marked, see Table 1. But still, more proofs in this principle is indispensable.

TEST GIRDER	MEAN VALUE OF LOAD F [kN]	LOAD RANGE [kN]	NUMBER OF LOAD CYCLES TO FAILURE
BTG 52	120	60	1 132 780
BTG 55	120	60	572 700
BTG 51	40	60	4 970 350

Table 1. Effect of the mean value of cyclic loading

A question now arises which value does the remaining carrying-capacity have, namely of the breathing girder webs being weakened by a fatigue crack. Since we have not observed any instabilized crack growth in the course of 1.test series, it remains to find a solution to the problem aforementioned, simply taking the equilibrium into consideration which several authors have resumed in the form of the so-called theory of tension field in the girder webs subject to shear. By virtue of test results and after introducing the tension field theory, the relationship was derived between the remaining shear carrying-capacity of the girders weakened by cracks and shear carrying-capacity of the unweakened ones, in the following form:

$$V_{res} = V_u\left\{1-\frac{d_{ec}}{d_w}\right\} = V_u\left\{1-\frac{d_c\cos\Theta + h_c\sin\Theta}{d_w\sec\Theta}\right\} \qquad (1)$$

At that, the angle Θ of a diagonal of the tension field is equal to the two thirds of the angle Θ_d of the girder web diagonal. Eq. (1) be based on the assumption that the remaining shear carrying-capacity is linear in relation to the ratio d_{ec}/d_w, ie in terms of the ratio of the effective depth of a fatigue crack d_{ec} to the web depth d_w.

3. Metal fatigue considerations

Before as early as 1900 some authors specified that the application of a mean tensile stress would decrease fatigue resistance, this approach being later rated by fatigue tests implemented on plain specimens at various mean stress levels, together with static tensile test particulars. The relationship on a given subject adopted from [2] is indicated in Fig. 1. Notwithstanding the philosophical difficulty of related static to dynamic fracture phenomena, the mentioned approach is widely accepted by industry though at high mean stress levels arising in many components (eg pre-stressed bolts) serious contradictions can be ascertained that may be explained merely by a crack growth analysis.

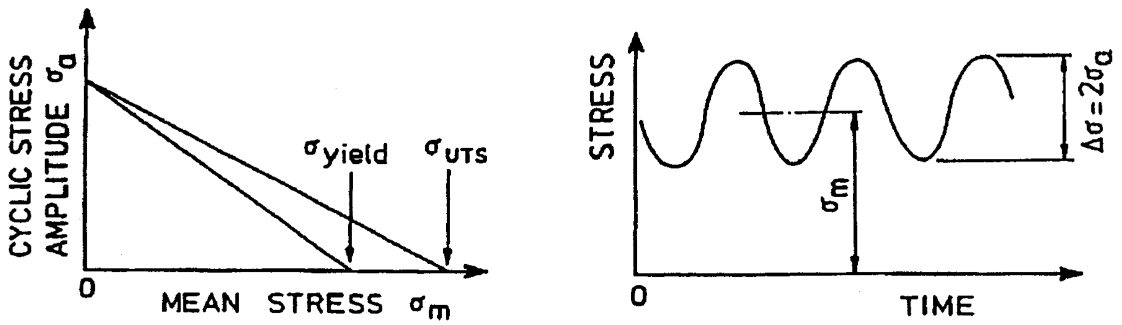

Fig. 1 Goodman diagrams and parameter specifications.

The reasons why a mean stress, σ_m can lessen fatigue resistance is that the maximum stress level in a constant $\Delta\sigma$ series of tests is increased and consequently the maximum crack tip opening displacement is enhanced; additionally the cyclic range of crack tip displacement is increased because crack closure on the elastic unloading part of a cycle can be excluded, and finally the environment has a much easier access and compensatory track to the plastically deformed zone at the crack tip. But still, giver cyclic torsion it is possible, with the crack sides of the Stage I shear cracks being left closed and thus the mean shear stress, τ_m, influence is not so outstanding and experimental results obey the depicted parabola more close at low R values ($R = \tau_{min}/\tau_{max}$). Of great attraction is the possibility of a periodic application of a tensile mean stress across the flanks of a shear directed crack since such loading conditions, frequently met in industrial components and structures (eg railway lines), may originate continuous Stage I crack growth without a transition to Stage II. To describe processes of crack initiation and propagation, six information entries are necessary:

1. Any sort of defect, no matter how small, represents a stress concentration (grain boundary, surface both inclusion and scratch) being at once a possible originator of the crack.
2. Fatigue crack are often watched below the fatigue limits of steels, these having grown but also subsequently arrested.
3. Micro- and macro-deformation responses with developed persistent slip bands may be immediately observed by optical and electron microscopes seeing that they are relatively large comparing to initial cracks which need only measure 0,1 x 0,1 microns but be difficult to find out.

4. The engineering definition of an initiated crack has been steadily reducing since the mid 19^{th} century from a length of several millimetres, to one millimetre, to 100 microns, to the size of a single grain, to a few microns (and in the event 0,1 microns or less?).
5. A crack of any size demands plasticity (movement of dislocations) to grow and should not require to wait for the establishment of a permanent slip band.
6. The acoustic microscope of late introduced may differentiate between a slip band and a crack.

In 1970, K.P. Zachariah assumed that the crack initiation period was zero and that the whole of lifetime was concerned with two phases of propagation namely (i) a short crack propagation phase (the beginnings of Microstructural Fracture Mechanics) and (ii) a longer crack growth phase defined in terms of EPFM. For a starter crack of two microns, the older definitions of "initiation" were dependent on the resolution of currently available microscopes. On top of it, the early growth rate of a crack far removed from various form of microstructural barriers is rapid but decreases on approaching a barriers. In due course, should all obstacles be overcome, a ruling crack can continue its propagation to failure and be described by continuum mechanics. The "initiation" zone is an initially fast but small propagating crack that may either accelerate, decelerate and arrest to acceleration, or decelerate and arrest to give fatigue limit. It will also be recognized why cracks can and do grow below any of the LEFM definitions of a threshold state. In fact, any size of defect or fatigue crack can propagate if the cyclic stress range is highish.

3.1 Construction

All structures, in particular welded ones, embrace large defects, ie a > 0.5 mm, together with stress concentration characteristics. Thankfully Tables of Stress Concentration Factors and Stress Intensity Factors exist but always these are in the main applied after a failure incident when the regions of weakness are obvious to all.

Fortunately the condition da/dN = 0 for structures may be analyzed from simple LEFM threshold conditions if an initial defect size D can be precisely estimated (which seldom succeeds in large welded structures). The major issues with engineering construction are, as follows:

(i) small stress concentration regions being located in large stress concentration zones, eg notches situated at the structure of 3D formulation

(ii) 3D in-service loading patterns being random in intensity, in orientation and acting in- and out-of-phase at different occurances in time

(iii) critical region for crack initiation not being recognized; note that fatigue cracks do not have to initiate at the worst stress concentration locations

In the next century, for that reason more analyses will be demanded for structures holding complex stress concentration, with cracks ranging in size from round about one to a few millimeters. This will be primarily true for those industries that usually have not yet introduced fracture mechanics into their design interpretations. It is certainly probable that many metal construction will be replaced by composite structures which have the aptitude to turn cracks aside from dangerous track.

3.2 Materials

Betterments in metals must and will go ahead, in particular in the composites and multiphase substances. It is to be hoped that material scientists and physicists will develop materials with thicker, stronger and more closely packed obstacles to micro-crack propagation. One can anticipate specific materials being designed and developed for specific utilizations, ie hindering the growth of Stage I and/or Stage II fatigue cracks depending on the application.

Since it is hoped that more accurate and flexible systems will be discovered to gauge and monitor the propagation of micron and submicron sized cracks (the acoustic microscope can size cracks of a few microns in length-but is miles away from being a mundane implement for industrial use). Multi-failures in electronic devices will help urge these developments.

It is awaited that dislocation theory will find a use, acceptable to engineers, in the development of models for determining the growth characteristics of cracks that are of a comparable size to dislocation aggregations. Who can guess – we may ultimately have a new science of Dislocation Fracture Mechanics.

Eventually, a note on the scatter of fatigue data. In the next century serious attempts will have to be made to present scatter in a proper perspective probably starting with the influences of different test variables on the

three fundamental fatigue limits. That is why, for laboratory tests on materials, the scatter of microstructural variables on Stage I cracks such as grain size, barrier thicknesses and strengths, now demand more detailed studies.
Regarding components, effects of slight changes in surface profiles and the surface texture are in want of separation whereas for structures the effect of minor variations in initial defect / crack sizes and external loading variables are very important. It needs to be recognized that a few overload cycles, a transient change in the environment and /or temperature (including thermal shock) may have a far more serious effect on tests to specify material behaviour and Stage I growth than, say, for a structure already weakened by a noticeable Stage II crack.

4. Conclusion

The initiation of the first fatigue crack means usually very little for the exhaustion of the actual fatigue life of girders with breathing webs. Moreover, the post-initiation residual lifetime very considerably varies as a function of the web geometry and of the intensity of repeated loading: it is small for very slender webs and high loads, but can be very large for the other cases. For webs of usual depth-to-thickness ratios and subjected to usually encountered load ranges, a design base on crack initiation would be conservative and would substantially reduce the competitiveness of steel in bridge and similar construction. Fatigue failure appears to be a more rational basis for the definition of the fatigue limit state of breathing webs because, from the point of view of the cumulative damage process, it is equally “just” for all girders - their geometry and loading level notwithstanding. In its light it is required that no fatigue failure shall occur before the planned fatigue life of the girder is fully exhausted - which is the objective of fatigue analysis. In the case of webs under the action of many times repeated predominantly shear, the maximum depth-to-thickness ratio of those webs for which the effect of breathing can be disregarded for all loading ranges is less than 175, and will be specified by further research.
Knowledge of the characteristics of cracks has become increasingly important especially as for their size, shape, orientation and growth rate together with their initial and final geometries.
The relevant developments in metal fatigue to be accomplished in the next century will be pertinent to the development of techniques to measure and continuously monitor fatigue cracks, inclusive of particularly those of 10^{-7} to 10^{-9} mm in size inside the metal.
For engineering components, the major tendency will be concerned with improvements to the fatigue resistance of surfaces.
In the case of structures, crack detection systems will be improved and significant advancements made owing to the effect of changing structural compliance on local crack growth characteristics. Ageing aircrafts, nuclear plants, long-life oil rigs and pipelines, fast ground-transport and ships, will present ever-increasing matters, but we hope that fracture mechanics, in all its forms, will progress for its early development stages and be put into practice with appropriate imperativeness in every branch of engineering industry.

5. Acknowledgement

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6. References

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