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New developments of the ESACRACK and FRAMES-2 software

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Summary

The European Space Agency (ESA) has developed and distributed since the mid-eighties the software packages ESACRACK and FRAMES-2.

A number of new developments to these packages are made in the framework of an ESA study addressing various aspects of structural integrity and fracture control of pressurised structures (this includes hardware under pressure, but also payloads inside pressurised modules of the Space Shuttle and International Space Station). Significant improvements in terms of user-friendliness and technical capabilities have been achieved.

In addition to the modifications of the software, additional guidelines and examples are developed, e.g. for application of the strip-yield crack-growth retardation model and development of fatigue spectra for Space Shuttle payloads.



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NEW DEVELOPMENTS OF THE ESACRACK AND FRAMES-2 SOFTWARE

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ABSTRACT

The European Space Agency (ESA) has developed and distributed since the mid-eighties the software packages ESACRACK and FRAMES-2.

A number of new developments to these packages are made in the framework of an ESA study addressing various aspects of structural integrity and fracture control of pressurised structures (this includes hardware under pressure, but also payloads inside pressurised modules of the Space Shuttle and International Space Station). Significant improvements in terms of user-friendliness and technical capabilities have been achieved.

In addition to the modifications of the software, additional guidelines and examples are developed, e.g. for application of the strip-yield crack-growth retardation model and development of fatigue spectra for Space Shuttle payloads.

1. INTRODUCTION

Nowadays, fatigue, fracture and safety critical components like pressurised structures are to be verified on the basis of damage tolerance requirements to prove their reliability under service loading conditions.

The damage tolerant design method for spacecraft structures and pressurised systems implies that the structure is designed such that stable crack growth will not become unstable (or cause e.g. leakage) during the service life (safe-life), or redundancy is introduced in the structure such that a part of the load path may fail without loss of overall structural integrity (fail-safe).

Damage tolerance for structures can be verified either by test or by analysis. The numerical tools ESA developed and distributed since the mid-eighties to verify the damage tolerance of spacecraft structures are available as the software packages ESACRACK and FRAMES-2. ESACRACK can be used for fatigue spectrum generation and fracture control analysis. FRAMES-2 is a data base system for storage, processing and retrieval of material properties and associated mechanical test results, specimen geometry and testing conditions.

ESACRACK consists of the modules:

- ESALOAD [1]: for fatigue spectrum derivation;
- NASGRO[®] [2]: a state of the art crack-growth analysis software originally developed by NASA, (with significant contributions made by ESA; its development is currently supported by the NASGRO Consortium);
- ESAFATIG [3]: for fatigue analysis of metallic structures.

This paper describes the new developments to the ESACRACK 4 and FRAMES-2 package performed within ESA contract "Structural Integrity of Pressurised Structures" (contract number 14923/00/NL/PA).

2. ESALOAD

ESALOAD is a software program that has been developed for the European Space Agency (ESA) to create a representative stress spectrum at the location of interest on a specific part of a space vehicle structure. Derived stress spectra can then subsequently be used in crack growth and/or fatigue analyses (using NASGRO[®] and/or ESAFATIG).

Fig. 1 gives an overview of the load and stress spectrum derivation in ESALOAD. On the basis of a selected event history, indicating the total number of handling, transport, test and flight events, a fatigue load spectrum can be generated. Predefined load curves (available in data bases), or calculated load curves, based on knowledge of the structural transmissibility and load input, can be used for the individual events.

The resulting load spectrum, defining all loads seen by a system or subsystem during its lifetime, can be transformed into a stress spectrum using unit stresses, i.e. stresses derived from knowledge of the structural response to unit loads.

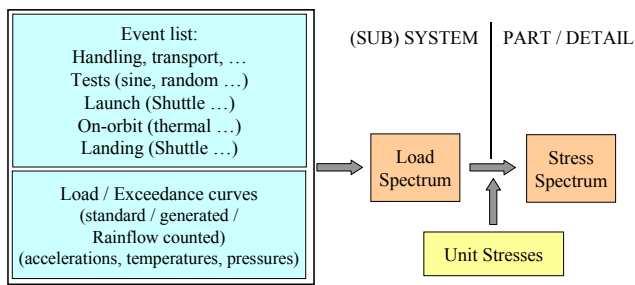


Fig. 1. Overview of ESALOAD load and stress spectrum derivation

In the frame of the ESA contract “Structural Integrity of Pressurised Structures”, various improvements have been made to the ESALOAD program. The major modifications concern:

- event generation and modification;
- load curve enhancements;
- transmissibility and load input definitions;
- unit stresses; and
- stress spectra generation.

Some minor modifications to the ESALOAD program are performed as well, like the possibility to define the maximum acceleration value used in the random load curve generation process, a reply of the effective (program used) Rainflow filter size, and the possibility to select multiple items. In all modifications, compatibility with previous versions is preserved.

Some of the major improvements are described in the following sections.

2.1 Load curve enhancements

The load curve consists of mean and alternating values of linear accelerations, pressure and temperature. This content has been extended to include rotational accelerations and a stress factor.

The possibility to include rotational accelerations was deemed necessary because they are in many cases defined as part of the loading environment for larger payloads.

The stress factor on additional stresses (see also section 2.2) was introduced for representation of prescribed interface displacements (but can be used to serve other purposes as well). For example: a standard way to store payload is to use the International Standard Payload Rack (ISPR), mounted inside a module of the International Space Station (ISS) (see Fig. 2). The mechanical connection between this module and the ISPR has a degree of redundancy of two. This means

that forces and stresses during launch and landing are not only related to the induced accelerations at the ISPR centre of gravity, but also to the displacements (or deformation) at the interface points between the module and the ISPR due to the coupled stiffnesses. Analysis has shown that these forces can contribute up to about 50% of the total interface force. Similar phenomena may be significant at other interfaces, e.g. internal interfaces of the integrated ISPR.

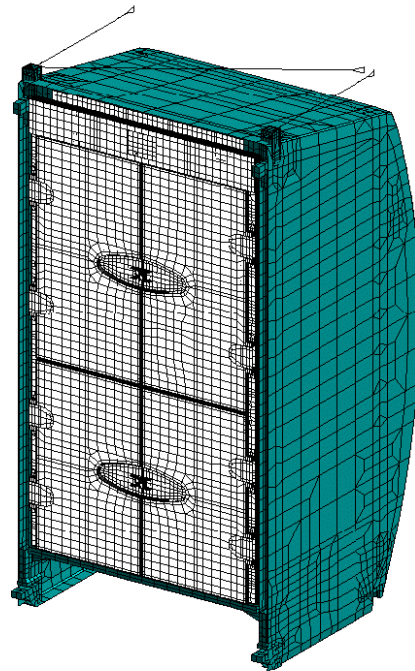


Fig. 2. Example of International Standard Payload Rack.

One possible way to overcome this is, is to include enforced displacements at the interface points (which would require the definition of unit stresses due to applied unit interface displacements). However, special care has to be taken to combine the dynamic loads due to these displacements with the centre of gravity accelerations. Another way to overcome this, and this is implemented in ESALOAD, is by means of location dependent additional stresses, caused by the enforced interface displacements. The stress factor, defined for each line of the load curve, is applied on the additional stress, which is part of the unit stress definition (see section 2.3).

2.2 Unit stresses per event

Unit stresses are defined as stresses (tension, bending, pin bearing, etc.) at the location of interest due to a unit load on the specific part for which load curves are derived. In ESALOAD, one set of unit stresses was



applicable to all load events, whether transport, test, shuttle ascent, etc.

In reality the unit stresses may be different for different events, due to e.g. different configurations (boundary conditions) during transport, test, launch/landing and/or on-orbit, or the fact that a local mode is important for the response of the structure due to random loads. Also, the preload and the newly introduced additional stresses may differ between launch, landing or other phases of the life of a structure (where they may be e.g. zero). Therefore, one major modification was to change ESALOAD with the capability to define unit stresses per event.

As mentioned in section 2.1, angular accelerations are included in the load curve. Therefore it is also necessary to extend the unit stress definitions with these three rotations.

Location dependent additional stress input is added to represent e.g. enforced interface deformation due to coupling with adjacent structures. A maximum and minimum stress can be defined in the unit stress definition menu, see Fig. 3. The additional stress variation, multiplied by the stress factor (see section 2.3), which is generally different for each line of a load curve, is considered as alternating stress in the stress spectrum derivation. The preload in the last line of Fig. 3 can be used to define a constant average stress. Use the additional stress if one wants to define mean and alternate stresses that vary with the stress factor.

Unit stresses [MPa] due to :	Tension	Bending1	Bending2	Point	Biaxial
X-acceleration	5.1	2.4	0.0000	0.0000	0.0000
Y-acceleration	3.1	1.5	0.0000	0.0000	0.0000
Z-acceleration	0.8	1.2	0.0000	0.0000	0.0000
Pressure	290.	33.	0.0000	0.0000	0.0000
Temperature	0.0000	0.0000	0.0000	0.0000	0.0000
X-acc. rotation	0.5	0.25	0.0000	0.0000	0.0000
Y-acc. rotation	0.5	0.25	0.0000	0.0000	0.0000
Z-acc. rotation	0.5	0.25	0.0000	0.0000	0.0000
Min-add. stress	0.0000	0.0000	0.0000	0.0000	0.0000
Max-add. stress	0.0000	0.0000	0.0000	0.0000	0.0000
Preload	0.0000	0.0000	0.0000	0.0000	0.0000

Fig. 3. Part of unit stress definition window.

2.3 New stress spectrum generation process

The process that is used to create a stress spectrum from the combination of a load spectrum and unit stresses in ESALOAD had to be changed considerably due to the significant number of newly added load components in the load spectrum.

The unit stresses are multiplied by the load factors of the load spectrum. However, it is clear that multiple loads, i.e. loads from different directions, may occur at the same time, but no information about their relative phase exists. As an assumption, stress components due to acceleration components (both linear and rotational) are evaluated in all possible combinations. This is not done for stresses due to pressure and temperature. Therefore only alternating acceleration components should normally be combined in one load line (mean loads of all types can be combined). This should not be a problem since they are normally related to different time constants.

Because of the inclusion of angular accelerations, a new stress generation procedure had to be developed and implemented in ESALOAD. Dependent on the load curve input, a stress spectrum generation processes will be performed. On a line-by-line basis the load curves are evaluated. When only linear accelerations and/or temperature and/or pressure are defined, i.e. rotational accelerations and stress factor are zero or undefined, the already existing stress spectrum generation process shall be used. When rotational accelerations and/or a stress factor are also defined, the “new stress spectrum generation process” is performed. This latter process is new to ESALOAD.

The load curve information consists of mean and alternating loads. By multiplying this with the associated unit stresses, mean and alternating stresses are determined.

The mean stresses are defined by:

$$\sigma_m = \sum_i [N_i \sigma_i] + \sigma_{add} + \sigma_c \quad (1)$$

In which N is the mean load and the σ unit stress. The i represents linear or rotational accelerations, pressure, or temperature. σ_c is the constant stress due to preload and σ_{add} is the mean additional stress that is determined by the mean of the maximum and minimum additional stress defined in the unit stress definitions, multiplied by the stress factor. This stress factor is defined in percentages, so 80 means 80% Therefore in ESALOAD the additional stress is multiplied by 80/100.



The alternating stresses are defined by:

$$\Delta\sigma_j = \sum_i [\pm \Delta N_i \Delta\sigma_i] \pm \Delta\sigma_{add} \quad (2)$$

in which the \pm sign indicates that the term $N_i\sigma_i$ is either added to or subtracted from the existing terms. Because there are seven independent variables (6 accelerations and the additional stress), the result is max. 128 alternating stresses (so $j = 1, \dots, 128$). The alternating additional stress is determined by multiplying the amplitude of the alternating additional stress with the stress factor from the load curve.

The introduction of the rotational accelerations and the stress factor increases the possible sign combinations from 8 (x, y and z) to 128 (x, y, z, Rx, Ry, Rz, additional stress) combinations for the alternating stress. This could cause an undesired increase in lines of the stress spectrum. In the next step, these 128 combinations are reduced to 4 lines using the approach already available in ESALOAD: find the maximum and minimum absolute values of these combinations, and divide this range into three equal ranges to come to 4 different alternating stress levels in the stress spectrum. The number of cycles assigned to each stress level is equally distributed over these stress levels, starting from the maximum stress.

2.4 Command file option

A command file option has been implemented in ESALOAD. This command file makes it possible to reduce the time spent on opening database and user files, automate the spectrum generation process, and it provides better traceability of how the spectra are derived.

The command file is an ASCII file that contains the list of actions for ESALOAD to open all required files and the actions to perform a load and stress spectrum generation. This file allows to automatically open a predefined list of ESALOAD input files (i.e. unit stresses, event file, load curve databases or transmissibility files), to select output files (i.e. load or stress spectrum) and to execute a combination of runs (load and/or stress spectrum generation with or without normalisation and compression) following a given order.

ESALOAD allows to create, edit and execute a command file thanks to a specific user interface, which facilitates the selection of files and definition of commands.

The import time domain data, the load curve generation and the event generation commands cannot be performed during the command file execution.

2.5 Extending user friendliness

The load curve modification and generation via the Graphical User Interface has been greatly improved in ESALOAD. For creating a new load curve (for instance for pressure or thermal tests) it was necessary to introduce load curves by hand in a text file or directly in the user load curve database file or project load curve database file. This is now possible from within the ESALOAD program. Additionally, adding the capability to modify load curves not only by column, but also by row or single element, and the possibility to add and delete rows increases the load curve data modification possibilities.

ESALOAD has the built-in capability to calculate load curves based on structural behaviour (transmissibility), test load input and flight load input. These transmissibility, test load input definition or flight load input definition are stored in files. The ESALOAD program has been changed to handle user-defined filenames, instead of using a predefined filename, and to change the contents of this file. Therefore it is also possible to use a different file for each analysis (project).

The ESALOAD user interface has been improved by increasing robustness but also providing new facilities as the multiple items selection throughout all ESALOAD lists.

User interface of flight data generation to event file has been improved when selecting/deselecting curves.

A facility to view and edit resulting load and stress spectrum files is now possible throughout ESALOAD.

In addition to the modifications of the software, additional guidelines and examples are developed for generation of fatigue spectra for Space Shuttle payloads.

3. NASGRO®

NASGRO®[2] is a suite of computer programs that can be used to

- calculate stress intensity factors, compute critical crack sizes, or conduct fatigue and sustained load crack growth analyses based on fracture mechanics principles. Material properties for crack growth can be picked up from a large database supplied with the program by selection from a menu of choices;
- solve complex two-dimensional geometries with or without cracks to obtain stress intensity factors and stresses via the boundary element method;



- enter, edit and curve-fit fracture toughness and fatigue crack growth data obtained in a laboratory.

Improvements to the NASGRO module include residual stresses from welding and three new stress intensity factors

In addition to the modifications of the software, additional guidelines are developed, e.g. for application of the strip-yield crack-growth retardation model.

3.1 Residual stresses from welding

As a result of the arc welding process and the subsequent cooling cycle(s) residual stresses are introduced near the welds.

The formation of these residual stress fields is complicated and, most certainly, has to be added to other residual stresses resulting from machining, rolling, etc.

In a previous version of ESACRACK [4] a residual stress option was implemented. It has not been available in the Windows version until now. It will be introduced again, with some small modifications:

- relaxation of the residual stress is performed assuming ideal plastic material properties, using either the yield strength from the materials data base, or a user-defined value (previously, the Ramberg-Osgood formulation was used, which requires an additional parameter);
- residual stresses are implemented in more cracked models than previously (TC06 to 08, SS01, SC02 to 05 are added to SC01 and TC01).

The main features of the residual stress implementation are briefly described below.

3.1.1 Residual stress distribution

Residual stresses are considered on a macroscopic level (also called residual stresses of the first kind). It has been assumed that these stresses are oriented in weld line direction. Residual stresses perpendicular to the weld line are assumed to be one order of magnitude smaller and, therefore, can be safely ignored.

In Fig. 4 a welded coupon is shown. The coordinate system and the relevant residual stress component are indicated in the section A-A'. The residual stresses $\sigma_{res}(x)$ are assumed to be of the following type

$$\sigma_{res}(x) = \sigma_o \left[1 - (x/RL)^2 \right] e^{-0,5(x/RL)^2} \quad (3)$$

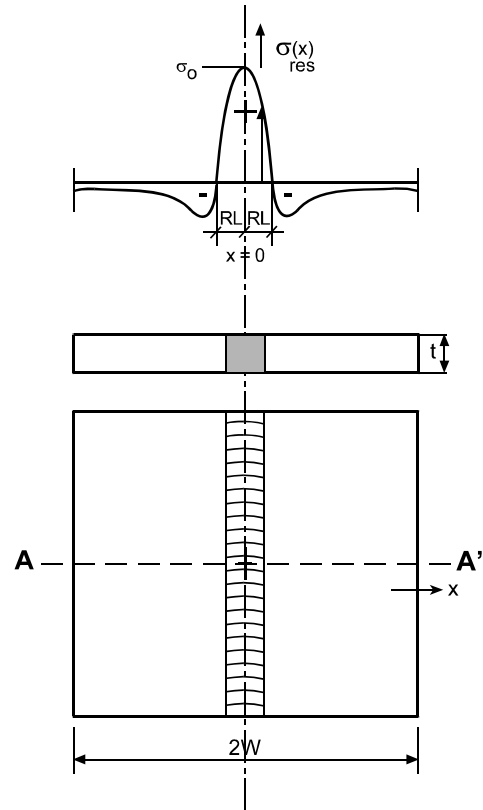


Fig. 4. Welded coupon with coordinate system and residual stress distribution

The maximum $\sigma_{res}(x)$ is assumed to be at the centre of the weld seam ($x=0$): σ_o . The zero crossing is at $x = \pm RL$. Eq. 3 is in principle valid for an infinite width W ($\sigma_{res}(x)$ tends to zero for infinite x ; equilibrium is not fully satisfied when W is finite). $\sigma_{res}(x)$ is constant in thickness direction. RL and σ_o are user-defined. If σ_o is not exactly known, it may be conservatively set equal to the yield strength: in case of high applied loads the residual stress will be reduced. In general, the approach is considered to be on the conservative side, especially since the beneficial effect on the stress intensity factor of compressive residual stresses, when the crack length exceeds $2RL$, is neglected.

3.1.2 Effects on the Stress Intensity Factor K

It is assumed that linear elastic (fracture) mechanics apply, therefore the Stress Intensity Factor induced by the residual stresses (K_{res}) can be simply added to the Stress Intensity Factor induced by other loading systems.

In a first step K_{res} is evaluated for a plate of infinite width. The effect of the residual stress distribution is determined by numerical integration over the crack surface (in 500 steps).



To this infinite width solution, a finite width correction is applied in the following way:

$$\begin{aligned} K &= F_0^c S_0 \sqrt{\pi c} + \text{the effect of other load systems} \\ &= F_0^c \tilde{K} + \text{the effect of other load systems} \end{aligned} \quad (4)$$

where F_0^c is a correction for the presence of free surfaces, such as finite width. \tilde{K} is the K factor solution for the infinite width configuration.

3.1.3 Effects on crack growth

The presence of residual stresses has an effect on K_{\max} and the load ratio R , but not on $\Delta K = K_{\max} - K_{\min}$. The crack growth laws of NASGRO generally include R to account for crack closure.

In view of the complicated effect in an application of the Strip-Yield model it is not allowed for the user to include residual stresses in combination with this model.

3.1.4 Relaxation of residual stresses by application of overloads

The introduction of the yield strength implies that yielding and residual stress relaxation occurs if high loads are applied.

In the present implementation of the residual stresses it is assumed that the yielding behaviour of the welded material is ideal plastic. In the original model the Ramberg-Osgood stress-strain curve was used. However, the corresponding material parameters are not present in the material databases. Therefore, it was decided to switch to ideal plastic behaviour and give the user the choice to use the yield strength given in the materials files as typical values (for the base or weld material) or user specified values. Note that the use of a too low value of the yield limit may lead to non-conservative results.

With this assumption yielding occurs when

$$\sigma_0 + S_{\max}^{(1)} \geq \sigma_y \quad (5)$$

In that case the parameter σ_0 in the description of the residual stresses is set to the value σ_0^{new} according to

$$\sigma_0^{\text{new}} = \sigma_y - S_{\max}^{(1)} \quad (6)$$

In Eq. 5 and 6, $S_{\max}^{(1)}$ is the first component in the loading system, which represents remote tensile loading

(bending will not give relaxation through the complete thickness and is therefore not considered).

Due to this relaxation of the residual stress when high loads are applied, it is not necessary to consider this stress in the net section stress calculation to determine the residual (ductile) strength.

3.2 New stress intensity factors

Three additional stress intensity factor (SIF) solutions were implemented in the NASGRO module of ESACRACK. The configurations are the following¹:

- TC20 represents a single edge through-the-thickness crack, loaded in tension/compression (S_0), bending in thickness direction (S_1), bending in width direction (S_2), and pin load on the crack surface (S_3). See Fig. 5.
- TC21 simulates a through-the-thickness crack growing through a riveted or bolted lap joint, starting from a hole and growing in one direction, loaded in tension/compression and pin loads. See Fig. 7.
- TC22 represents a simple T-section beam, loaded in tension/compression and bending, where a single through-the-thickness crack starts in the top of the web and grows into both flanges (base part). See Fig. 9.

These three SIF solutions are currently under development, but some details about this implementation are described in the following sections.

3.2.1 Case TC20: Edge crack loaded by a pin load

The configuration for TC20 represents a through-the-thickness edge crack loaded by a pin load and is shown in Fig. 5. It is identical to a through-the-thickness crack at the edge of a plate (TC02), except that a pin load is added.

The stress intensity factor K for this model equals the stress intensity factor of TC02 (edge crack), superimposed by the K for a single edge through crack under a point load. This K is derived in [5], page 2.29.

¹ These new stress intensity factors will be available in the near future, but initially only in NASGRO 3.

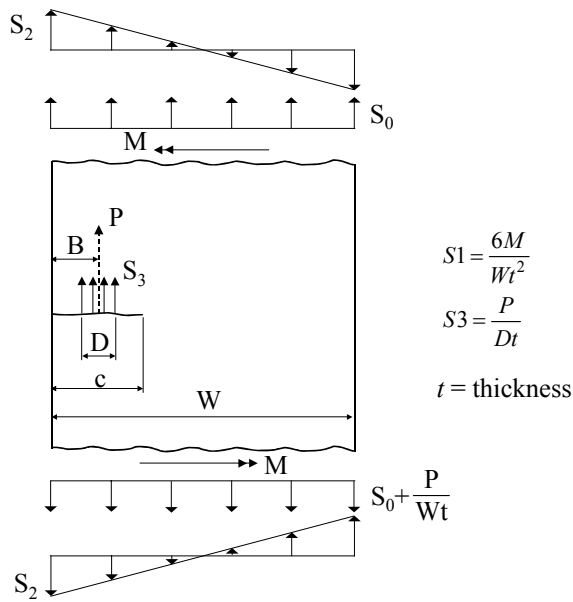


Fig. 5. Pin load acting on an edge crack in a finite width sheet specimen (TC20)

The net section stress definition for TC20 consists of the net section stresses of TC02 (see Appendix B of [2]), superimposed with the pin load S_3 to arrive at the net section stress of TC20. This additional terms σ_{a3} and σ_{b3} are the stress caused by S_3 due to a reduction of the cross-sectional area and bending stress caused by S_3 due to asymmetry of the crack location, and are defined as:

$$\begin{aligned} \sigma_{a3} &= S_3 \frac{D}{W-c} \\ \sigma_{b3} &= S_3 \frac{6D}{(W-c)^2} \left(\frac{W+c}{2} - B \right) (1-2\varepsilon) \end{aligned} \quad (7)$$

in which ε is the fraction of the uncracked ligament from outer boundary at which bending stresses are calculated (set to 0.13, see Appendix B of [2]).

Under the assumption that the effect of the hole on the crack growing out of the hole, while the other side is already cracked, can be neglected, this SIF solution allows continuing the crack growth calculation of a through crack from an offset hole in a plate (TC03) for spectra containing pin loads (S_3), see Fig. 6.

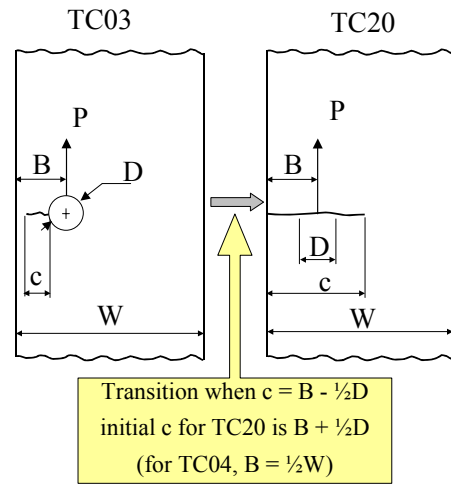


Fig. 6. Continuation of TC03 to TC20

3.2.2 Case TC21: Crack loaded by a variable series of pin loads

The TC21 configuration represents a through the thickness crack loaded by a variable series of point loads (i.e. extending over a number of fastener holes), see Fig. 7. In the implementation of the SIF solution it is assumed that the crack tip on the one side stays at the edge of the rivet hole (no growth at this tip). For the crack tip on the other side it is assumed that the crack jumps over the diameter of the rivet when the crack tip enters a rivet hole. For simplicity, it is also assumed that the holes have no effect on the crack growth.

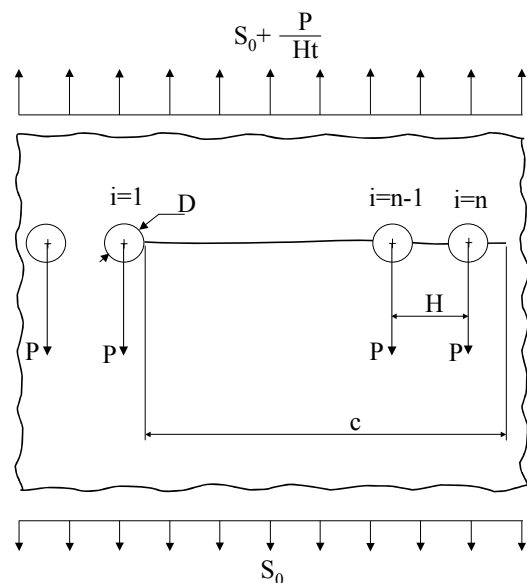


Fig. 7. Crack growth through an area where pin loads are acting (TC21)

