

# Residual life of steel structures and equipment: problems and application to cranes

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**Abstract.** The paper starts by considering, in general, the problem of evaluating residual life of structures and equipment that may have reached or exceeded the end of their design life. Whilst the problem is encountered in many industrial sectors, references available for dealing with it are often limited. Selected European references potentially suitable for this purpose for steel structures and cranes are presented and discussed in this paper together with some of the practical problems faced by the engineers responsible for evaluating the residual life of equipment and structures. This includes an overview of FEM Crane Codes and European EN standards for steel structures and cranes, their methods for assessing fatigue lives and their application to evaluating residual lives. A procedure developed in France and in use for such purpose since 2003, an approach developed in Italy and approach taken by ISO 12482 standard are all reviewed next. Finally, the paper presents a general methodology for the assessment and management of residual life of existing equipment and structures that has been developed by CETIM (Technical Institute for Mechanical Industry) and concludes with an example of its application to an AIRBUS load manipulating device.

**Keywords:** Design life / fatigue life / residual life / evaluation / steel structures / cranes

## 1 Introduction

When an existing equipment or a structure has reached or exceeded its design lifetime presumed by the manufacturer, its owner has legitimately to ask himself crucial questions, such as:

- Can I still continue to use it as it is now and without danger?
- And, if so, for how much longer?

There exist methodologies, supported by established rules or standards that can answer such questions but not in a systematic form; it depends on the type of equipment and frequently with no specific references existing.

Moreover, most of the rules or standards dedicated to the design of structures or machines are only intended for the determination of lifetime, at a design stage and not all of them can be easily applied to the case of an old equipment, for which an extension of the service lifetime is sought because keeping the equipment in operation may be desirable, e.g. for economic reasons. Such extension may increase the risk of fatigue failures.

However, it is not possible to support such an extension by the use of non-destructive testing (NDT) that cannot quantify the fatigue damage of material without a crack being present.

The assessment should calculate the residual life of the equipment and determine the details of future inspections, and eventually derating and/or repairs.

This paper gives an overview of existing references in Europe and France applicable to the problem of residual life, mainly of steel structures and cranes.

It then presents a specific methodology to extend safely the service lifetime of industrial equipment developed by CETIM (Technical Institute for Mechanical Industry).

Finally, cases of cranes and runways are discussed, and an illustration is given of an application to load manipulating devices for AIRBUS.

## 2 Ageing of equipment: few figures

All over the world, many structures, machines or equipment built decades ago are now in derated or “fatigued” conditions. They may exhibit signs of local defects which prevent them from serving fully their initial purpose; the local defects can be cracks, corrosion, excessive deformation, functional obsolescence, and so on.

For example, at the moment, there are hundreds of thousands of steel bridges in Europe and according to surveys made for the European market only, more than half of the budget for the development of infrastructure is for the maintenance and modernization of the existing one while less than a half is for extension and renewal [1].

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**Table 1.** Description of damages for national roads bridges in Indonesia.

Condition	Description	Units	%
0	Good condition	10,047	47
1	Few damage (damage can be repaired through routine maintenance, and do not affect the safety or function of the bridge)	4,274	20
2	Damage that requires monitoring or maintenance in the future	3,419	16
3	Many damage that need to be rehabilitation next years	1,709	8
4	Critical condition	854	4
5	Collapsed or is not be functioned	1,068	5

**Table 2.** Typical fatigue damage on steel structures of inspected Vietnam railway bridges.

Fatigue damage	Occurrences	Degrees	Main causes
Cracks of welded lines and weaken locations	Frequent (80% bridges)	Serious	Traffic overloads (increased weights and speeds) as well as structural vibrations of modern trains impose on railway bridges
Over-sags of bridge decks and girders	Frequent (60% bridges)	Moderate	Exceeded collisions of large moving trains and vessels against railway bridges
Over-displacement of steel elements	Sometimes (40% bridges)	Moderate	Other causes of missiles, bombs and explosions due to the wars
Joint breaking and damage of steel joints	Sometimes (30% bridges)	Moderate	External impacts, natural disasters and so on

In Indonesia, 23% of the 88 000 existing bridges are more than 50 yr old and with 53% of the bridges exhibiting damage, distributed as illustrated in Table 1 [14].

In Vietnam, 68% of the existing railway bridges are said to have been built before 1954, 17% of them are steel bridges and Table 2 details the reported fatigue damage, affecting up to 80% of the steel bridges [13].

In Egypt, 32% of bridges are more than 100 yr old and 20% of them are in bad to severe condition [15].

If we deal with cranes that also have a steel structure, a study specific to the Chinese market shows a relatively long service life of portal cranes and that some continue to be used with a life extension. For instance, from portal cranes discussed in [2] that are more than 20 yr old, 89% of them exhibited fatigue cracks.

### 3 Residual life of existing steel structures

#### 3.1 Proof of fatigue strength of steel structures in Europe: Eurocodes

The Eurocodes consist of ten European EN standards (EN i.e. harmonized technical rules/standard of the European Union) the purpose of which is notably to provide means of proving a compliance with the requirements for mechanical strength. Since March 2010 the Eurocodes have been mandatory for the specification of public works within the European Union, therefore replacing the existing national building codes published by national standard bodies (e.g. CM 66 in France or DIN 4114 in Germany).

Below is a limited selection of the fifty eight EN parts of the Eurocode dealing with bridges or cranes, including

fatigue strength (load actions and proof):

- Eurocode: *Basis of structural design* (EN 1990)
- Eurocode 1: *Actions on structures* (EN 1991)
  - Part 2: Traffic loads on bridges (EN 1991-2)
  - Part 3: Actions induced by cranes and machinery (EN 1991-3)
- Eurocode 3: *Design of steel structures* (EN 1993)
  - Part 1-1: General rules and rules for buildings (EN 1993-1-1)
  - Part 1-9: Fatigue (EN 1993-1-9)
  - Part 2: Steel Bridges (EN 1993-2)
  - Part 6: Crane supporting structures (EN 1993-6)

Concerning Fatigue, EN 1993-1-9:2005 presents general requirements and methods for the proof of fatigue strength of steel structures [5].

The proof of fatigue strength in accordance with EN 1993-1-9 (see also the IIW Recommendations [3]) deals predominantly with the nominal stress approach, based on a global stress analysis method and uses the concept of nominal stress ranges  $\Delta\sigma_n$ , determined from loads and relevant cross section properties, together with a set of  $\Delta\sigma_{R-N}$  curves corresponding to main construction details (see Fig. 1).

This is a basic and widely used design method, based on the results of extensive laboratory fatigue tests aimed at providing probabilistic design S-N (Stress-Life) curves (for a required probability of survival, e.g. 97.7% probability of survival in this case).

The local structural stress (also called hot-spot stress or geometric stress) approach, taking into account only the part of stress concentration related to the structural

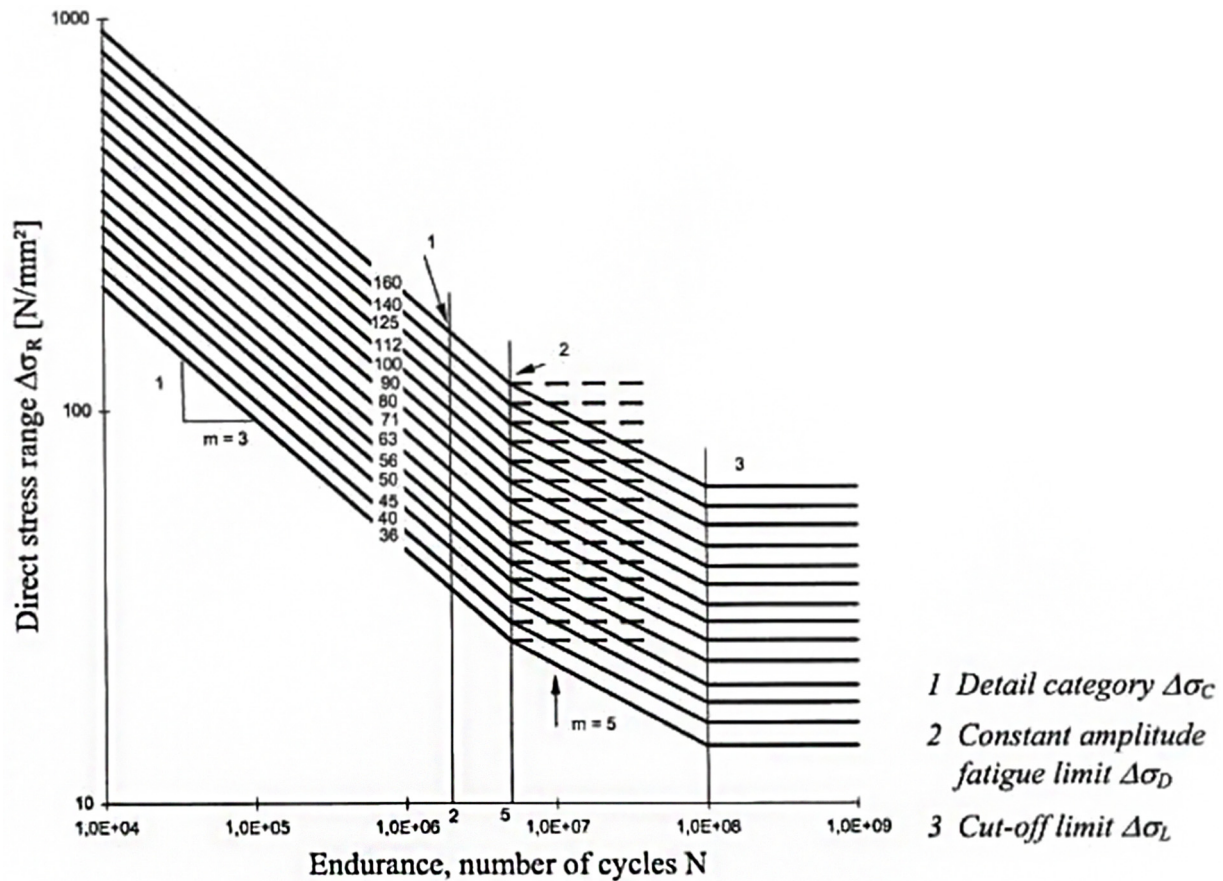


Fig. 1. Fatigue strength curves for direct stress ranges (EN 1993-1-9:2005, Fig. 8.1).

geometry (macro-geometry) but not the local stress raising effect of the weld itself, is also dealt within EN 1993-1-9.

### 3.2 Residual life of steel structures: JRC Scientific and Technical Report EUR 23252 EN (2008)

During the 1990s, many studies focused on the assessment of existing steel structures, mainly those predominantly exposed to fatigue loading such as bridges or crane supporting structures. These works have resulted in a better understanding of the behaviour of existing structures and to an assessment method described below.

This evaluation method, respectively structure assessment, can be divided into four phases as illustrated in Figure 2.

#### Phase I: preliminary evaluation

The aim is to remove all existing doubts regarding the safety of the structure utilizing simple methods and identify critical components or parts of the structure. This is done by collecting information on the structure such as engineering drawings, design calculations, structure surveys and inspections, etc.

Assessments are carried out by the engineer alone.

#### Phase II: detailed investigation

The aim is to update the information on the structure and carry out an evaluation of the individual components of the structure identified as potentially unsafe.

This is carried out with a quantitative control (e.g. NDT), using updated loads, strengths and accurate models.

Technical experts and specialists may be required to carry out this assessment, in addition to the engineer.

#### Phase III: expert investigation

A team of experts should be invited to review and check the conclusions reached in **Phase II**. They may provide additional assessments by using specific tools (i.e. probabilistic methods, fracture mechanics, etc.) as well as further discussion in order to assist in decision making.

#### Phase IV: remedial measures

The aim is to propose measures that ensure operational safety of the structure during an extended period of use.

Various measures may be adopted such as increased monitoring of structure, reduction of loads, change in use/duty, strengthening, repairs or refurbishment.

The proof of the relevance of the measures to be taken to ensure safety shall be demonstrated.

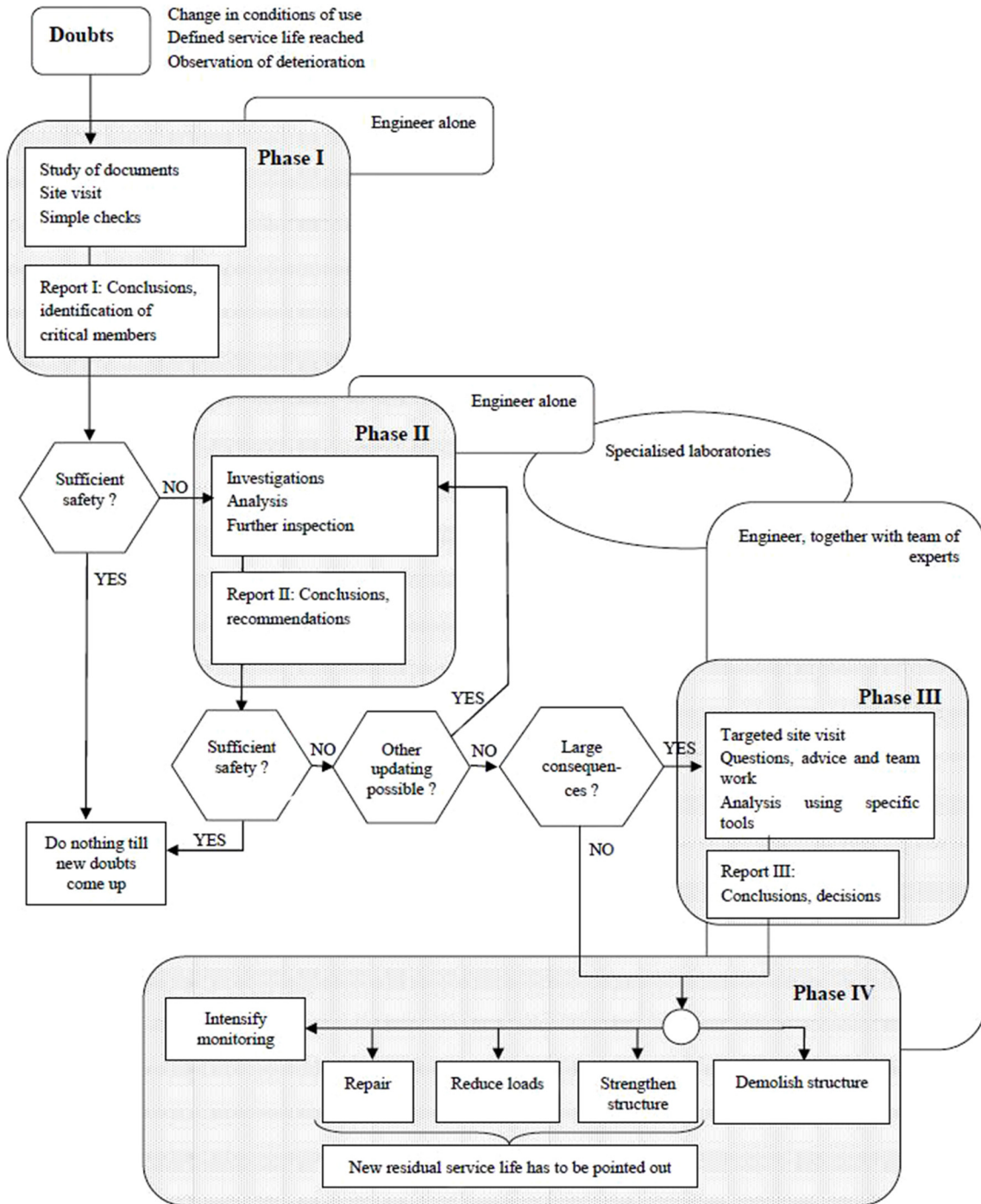


Fig. 2. Illustration of the four phases general assessment procedure (EUR 23252 EN, Figs. 1-7).

JRC Scientific and Technical Report EUR 23252 EN is linked to EN 1993-1-9 for fatigue verification using S-N curves (phases I, II) and it also deals with fracture mechanics and probabilistic methods (phase III).

Unfortunately, those recommendations have not yet been translated into an EN standard and they are not expected to be revised for many years.

However, they provide a methodology that can be applied to other equipment than steel structures.

#### 4 Crane design, residual life of cranes and related rules and standards

This section presents a selection of relevant European rules and standards, dealing either with crane design or with the assessment of residual life of cranes. The list is not exhaustive.

First are the rules or standards that are mainly used in Europe for crane design, but potentially an estimation of residual fatigue life of a crane could be based on them,

Case K2 - Medium stress concentration (continued)

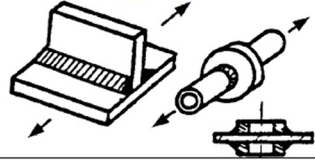

Reference	Description	Figure	Symbol
2,2	Continuous main member to which transverse diaphragm, web stiffeners, rings or hubs are fillet welded (S.Q.) at right angles to the direction of the forces		

Fig. 3. Example of a constructional detail from FEM 1.001.

especially if they were used for its original design. For instance, such consistency may be required when the estimation forms a part of a judicial appraisal.

This is why we present very briefly the procedure of a proof of fatigue strength, for each of them.

#### 4.1 Crane design

##### 4.1.1 FEM 1.001, Rules for the design of hoisting appliances (1998, 3rd edition)

The rules for the design of hoisting appliances drawn up by the Technical Committee of Section I of the F.E.M. (*Fédération Européenne de la Manutention*, European Handling Federation) were first published in 1962. In this first version, the method for a proof of fatigue strength was based on:

- the global classification of the crane (classes **I**, **II**, **III** and **IV**),
- the global classification of each mechanism (classes **I<sub>m</sub>** to **IV<sub>m</sub>**),
- the constructional details, classified in six groups (two unwelded-members categories and four welded-members categories) and with a limited number of constructional details.

The second edition published in 1970 refined the method with:

- six classes (designed by **1** to **6**) of structural components,
- eight categories (three unwelded-members categories **W** and five welded-members categories **K**), with more constructional details.

For the proof of fatigue strength of mechanisms and their components based only on an infinite or high cycle fatigue life, mechanisms were classified into six groups.

The final version of the FEM Rules (1987 edition together with supplements and comments published in 1998, [7]) stabilized the proof of fatigue strength basing it on:

- eight groups of crane (structural or mechanism) components, designed by **E1**, ..., **E8**, on the basis of:
  - their class of utilization : *total number of stress cycles* to which the component is subjected (classes **B0**, ..., **B10**),
  - their class of stress spectrum (classes **P1**, ..., **P4**), depending on the value of the *stress spectrum factor*  $k_{sp}$  with a value ranging from 0 to 1.0;

- eight categories of constructional details (three categories **W** for unwelded-members and five categories **K** for welded-members).

The values of the total number of stress cycles and of the stress spectrum factor are specific to different locations and stress points on a crane structure. These values are related to crane duty and decisively depend on:

- the number of working cycles,
- the net load spectrum,
- crane configuration,
- the effect of the crane motions on stress variations (traverse, slewing, luffing, etc.).

An example of a constructional detail from the FEM Rules, in this case the design detail 2,2 belonging to the construction cases **K2** (medium stress concentration), is presented in Figure 3.

Key information for the proof of fatigue strength in accordance to FEM 1.001 is presented in Figure 4; it gives the permissible fatigue stress  $\sigma_w$  for the detail under consideration (under constant alternating stress), depending on:

- the component group **E** it belongs to, representing the fatigue damage due to its stress spectrum,
- its construction case, either **W** or **K** type, representing the sensitivity to the stress concentration (welded members) and the material endurance limit (for unwelded members).

In the final proof, the maximal normal stress  $\sigma_x$  shall be compared to the permissible stress for fatigue  $\sigma_{xA}$ , calculated from  $\sigma_w$ .

FEM Rules have been widely used in Europe, but nowadays they can be considered to be an ageing state of art.

##### 4.1.2 DIN 15018-1 Cranes — Principles for steel structures, stress analysis (1984)

DIN 15018 [12], defining the design rules for crane structures under static and fatigue loads, was first published in 1974 replacing the old DIN 120 (1936). Its second version was published in 1984.

Concerning the proof of fatigue strength, there are procedural similarities between DIN 15018 and FEM 1.001 and the construction cases are identical: denoted as **W0**, **W1**, **W2** for single plates and bolted connections and **K0** to **K4** for welded connections.

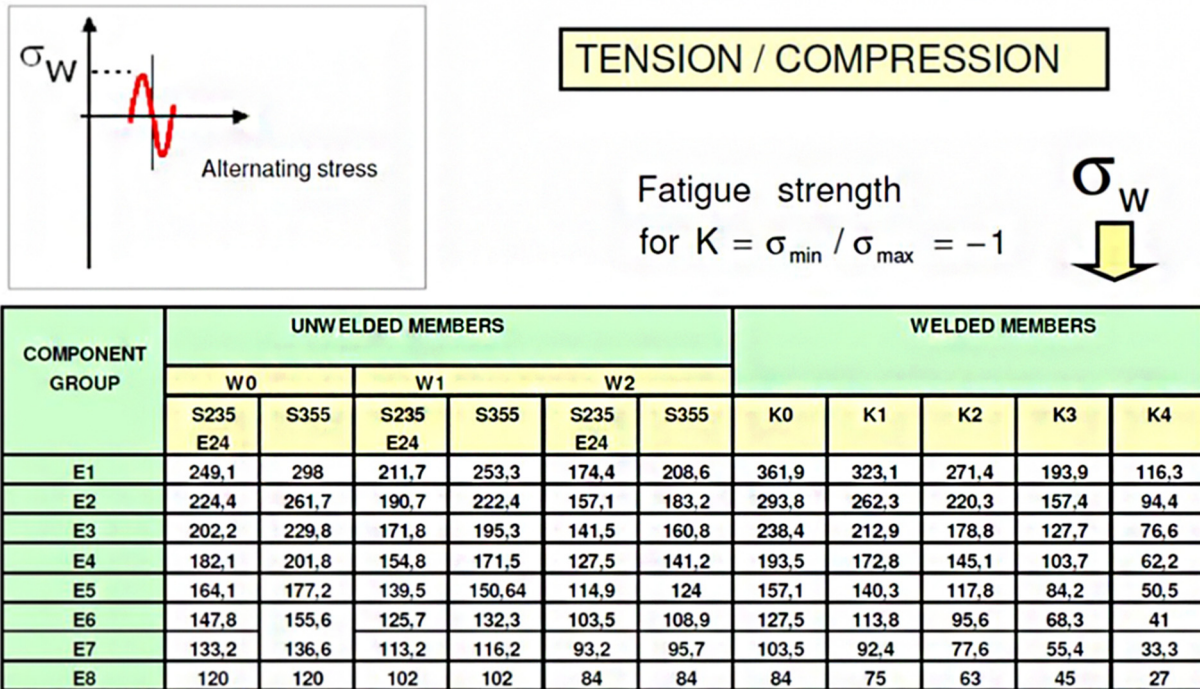


Fig. 4. Values of  $\sigma_w$  [N/mm<sup>2</sup>] depending on the component group and construction case, Table T.A.3.6.1.

However, structural components in DIN 15018 are classified in six groups of components, designated as **B1**, ..., **B6**, on the basis of

- their class of utilization: total number of stress cycles to which the component is subjected (classes **N1**, ..., **N4**),
- their class of stress spectrum (classes **S0**, ..., **S3**).

DIN 15018 has also been widely used in Europe until it was officially replaced by the EN 13001 series of standards in 2012.

#### 4.1.3 EN 13001, Crane design (series of standards, published since 2003)

##### 4.1.3.1 Machinery directive

In 1989 was published the first version of the Machinery Directive (current version is Directive 2006/42/EC), concerning machinery and some parts of machinery. Its main intention is to ensure a common safety level in machinery placed on the market or put in service in all EU member states and to ensure freedom of movement within the European Union by stating that “member states shall not prohibit, restrict or impede the placing on the market and/or putting into service in their territory of machinery which complies with [the] Directive”.

The particularity of such Directives is that they set the basic requirements or Essential Health and Safety Requirements (EHSR) that apply to all manufacturers who wish to put their products on the market of the European Union. If a product meets the essential Health and Safety Requirements, then the product can be placed on the EU market.

A way of demonstrating compliance with the Essential Health and Safety Requirements is by compliance with

harmonized European standards or by any other means that demonstrates a similar level of safety.

##### 4.1.3.2 EN 13001 series of standards

In 1989, CEN (*Comité Européen de Normalisation*, i.e. European Committee for Standardization) created the Technical Committee 147 in charge of developing and maintaining safety standards for the design, manufacture and information to be provided for the following products:

- cranes;
- equipment for the lifting of persons with some cranes;
- power driven winches and hoists, and their supporting structures;
- hand-powered lifting machines;
- non-fixed load lifting attachments;
- manually controlled load manipulating devices.

Within TC147, working group WG2 has been in charge of the development of the EN 13001 series of standards dealing with crane design and giving the presumption of conformity to the Machinery Directive.

FEM 1.001 Rules and DIN 15018 cannot give such presumption because they had been developed and issued prior to the first publication of the Machinery Directive, in 1989.

The parts of EN 13001, *Cranes – General design*, are as follows:

- *Part 1: General principles and requirements;*
- *Part 2: Load actions;*
- *Part 3-1: Limit states and proof of competence of steel structures;*
- *Part 3-2: Limit states and proof of competence of wire ropes in reeving systems;*

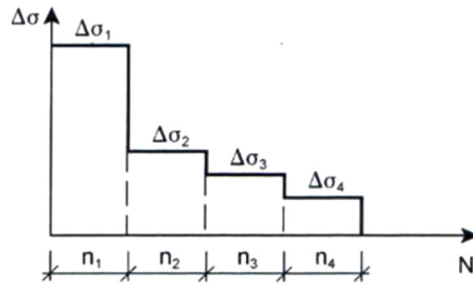


Fig. 5. Stress spectrum, principles.

- Part 3-3: Limit states and proof of competence of wheel/rail contacts;
- Part 3-4: Limit states and proof of competence of bearings;
- Part 3-5: Limit states and proof of competence of forged hooks;
- Part 3-6: Limit states and proof of competence of machinery – Hydraulic cylinders.

In TC147, there are also product standards that are developed for specific types of cranes and that can include requirements for design, in combination with EN 13001 series of standards (e.g. EN 15011 for bridge and gantry cranes or EN 13852 for offshore-cranes).

If we consider EN 13001-3-1 “steel structures”, it is to be used together with EN 13001-1 and EN 13001-2 and as such they specify requirements and methods to prevent mechanical hazards of cranes, such as:

- exceeding the limits of strength (yield, ultimate, fatigue);
- exceeding temperature limits of material or components;
- elastic instability of the crane or its parts (buckling, bulging).

EN 13001-3-1 was firstly published as Technical Specification (CEN/TS, experimental standard not giving presumption of conformity to Machinery Directive) in 2005 and it became a harmonized EN standard in 2012.

#### 4.1.3.3 EN 13001-3-1: proof of fatigue strength, principles

There are similarities as well as differences between the proofs executed in FEM 1.001 Rules and EN 13001-3-1 Standard.

One of the similarities is notably that the component under consideration has to be classified in a component group depending on its design fatigue damage, however there is no more classification of mechanisms in EN 13001 (as M-groups in FEM 1.001 Rules) because the notion of time-based classification is obsolete.

The classification of structural components in EN 13001-3-1 results in twelve groups of components (for eight groups in FEM Rules), designed by **S02**..., **S9**, on the basis of their stress history parameter **s** (expression of the fatigue damage).

This parameter **s** is the product of:

- the relative total number **v** of stress ranges  $\Delta\sigma_i$  (total number of stress ranges divided by  $2 \times 10^6$ );
- the stress spectrum factor **k**, depending on **m** (slope constant of the log  $\Delta\sigma - \log N$ -curve of the component under consideration), calculated from the stress spectrum (see example in Fig. 5).

DIN 15018 $s=0,0019$	FEM 1.001 FEM 2.131 2.132	pr EN 13001-1
$s=0,0055$ <b>B1</b>	$s=0,0067$	$s=0,008$ <b>S0</b>
$s=0,0156$ <b>B2</b>	$s=0,0126$ <b>E1</b>	$s=0,016$ <b>S1</b>
$s=0,0446$ <b>B3</b>	$s=0,0236$ <b>E2</b>	$s=0,032$ <b>S2</b>
$s=0,1250$ <b>B4</b>	$s=0,0440$ <b>E3</b>	$s=0,063$ <b>S3</b>
$s=0,3535$ <b>B5</b>	$s=0,0822$ <b>E4</b>	$s=0,125$ <b>S4</b>
$s=1$ <b>B6</b>	$s=0,1535$ <b>E5</b>	$s=0,25$ <b>S5</b>
	$s=0,2867$ <b>E6</b>	$s=0,5$ <b>S6</b>
	$s=0,5354$ <b>E7</b>	$s=1$ <b>S7</b>
	$s=1$ <b>E8</b>	$s=2$ <b>S8</b>
		$s=4$ <b>S9</b>

Fig. 6. Components groups in DIN 15018 vs. FEM 1.001 vs. prEN 13001-1 (2005).

Figure 6 illustrates the relative positioning of the parameter **s** corresponding to limit values of the component groups **B** (DIN 15018), **E** (FEM 1.001) and **S** (EN 13001 in 2005 version that included ten classes **S** instead of twelve, currently) and for a slope constant of the S-N curves set equal to **m** = 3.

Whereas in EN 13001-3-1, the proof of fatigue strength of structural components is based on stress ranges FEM Rules that take into account mean stress value into their consideration, which is not a common practice nowadays for welded structures in as-welded condition.

The stresses are calculated in accordance with the nominal stress concept and hot spot stress is not dealt by EN 13001.

The method includes for fatigue strength a specific resistance factor  $\gamma_{mf}$  depending on:

- accessibility of the detail,
- fail-safe/non fail-safe category.

The limit design stress of a constructional detail is characterized by the value of  $\Delta\sigma_c$  (normal stress range) or  $\Delta\tau_c$  (shear stress range), characteristic fatigue strength at  $2 \times 10^6$  cycles under constant stress range loading and with a probability of survival equal to 97.7%.

The values of characteristic fatigue strength are given in five tables for:

- Table D.1: Basic material of structural members;
- Table D.2: Elements of non-welded connections;
- Table D.3: Welded members;
- Table H.1: Connections and joints of hollow section girders;
- Table H.2: Lattice type connections of hollow section girders.

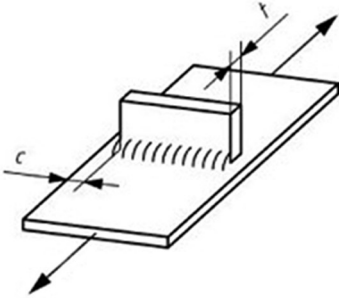
Detail No.	$\Delta\sigma_c$ $\Delta\tau_c$ N/mm <sup>2</sup>	Constructional detail	Requirements	
3.28	m = 3	 <p>Continuous component to which parts are welded transversally</p>	<p>Basic conditions:</p> <ul style="list-style-type: none"> <li>— plate thickness <math>t \leq 12</math> mm</li> <li>— <math>c \geq 10</math> mm</li> <li>— quality level D not allowed for K-weld</li> </ul> <p>Special conditions:</p> <ul style="list-style-type: none"> <li>— plate thickness <math>t &gt; 12</math> mm (Double fillet welds only) -1 NC</li> <li>— <math>c &lt; 10</math> mm -1 NC</li> <li>— K-weld instead of double fillet weld +1 NC</li> <li>— quality level D instead of C -1 NC</li> </ul>	
			112	Double fillet weld, quality level B*
			100	Double fillet weld, quality level B
			90	Double fillet weld, quality level C
			80	Single fillet weld, quality level B, C
			80	Partial penetration V-weld on remaining backing, quality level B, C

Fig. 7. Example constructional detail from Table D.3 (EN 13001-3-1).

Due to the capitalization of all the fatigue tests performed in Europe for thirty years, those tables provide more details than FEM 1.001 Rules and DIN 1518, with basic or deviating conditions and taking into account the weld quality class B, B\*, or C (in accordance with EN ISO 5817).

Figure 7 shows a constructional detail (Number 3.28 from Table D.3) which is comparable with one detail in Figure 3 (FEM Rules).

Final proof of fatigue strength shall be executed using the following condition:

$$\Delta\sigma_{sd} < \Delta\sigma_{Rd} = \frac{\Delta\sigma_c}{\gamma_{mf} \cdot \sqrt[m]{s}},$$

where  $\Delta\sigma_{sd}$  is the maximum stress range from the stress spectrum and where  $\Delta\sigma_{Rd}$  is the limit design stress range.

## 4.2 Residual life of cranes

By comparison to the references dealing with crane design, references dealing with the evaluation of the residual life of cranes seem to be rare.

Following are the only relevant ones that we could collect.

4.2.1 Recommendations applicable to "old" port cranes, CETMEF Technical Guide (France, 2003)

### 4.2.1.1 Background

In the 1990s, many accidents and incidents were reported in French ports. Most of them were linked to old cranes; at that time more than 70% of the port cranes were more than 20 yr old.

The crane manufacturers were reluctant, for reasons of legal responsibility, to suggest procedures for assessment of old cranes because the maintenance is under the control of the port service activities.

This led the managers of the port service activities to investigate if there were existing specific references dealing with assessment of old cranes.

On the request of the Maritime Transport Board, a working group was created at national scale, including engineers from two institutes (CETIM – Technical Institute for Mechanical Industry, LCPC – Central Laboratory of Structural Engineering), port service activities, plus some consultants.

In the absence of an adequate standard, the working group decided to develop its own procedure, mentioning only, as external references:

- ISO 12482 – 1, *Cranes – Condition monitoring* (1995, see 4.2.3 below),
- FEM Rules 1.001 (1998).



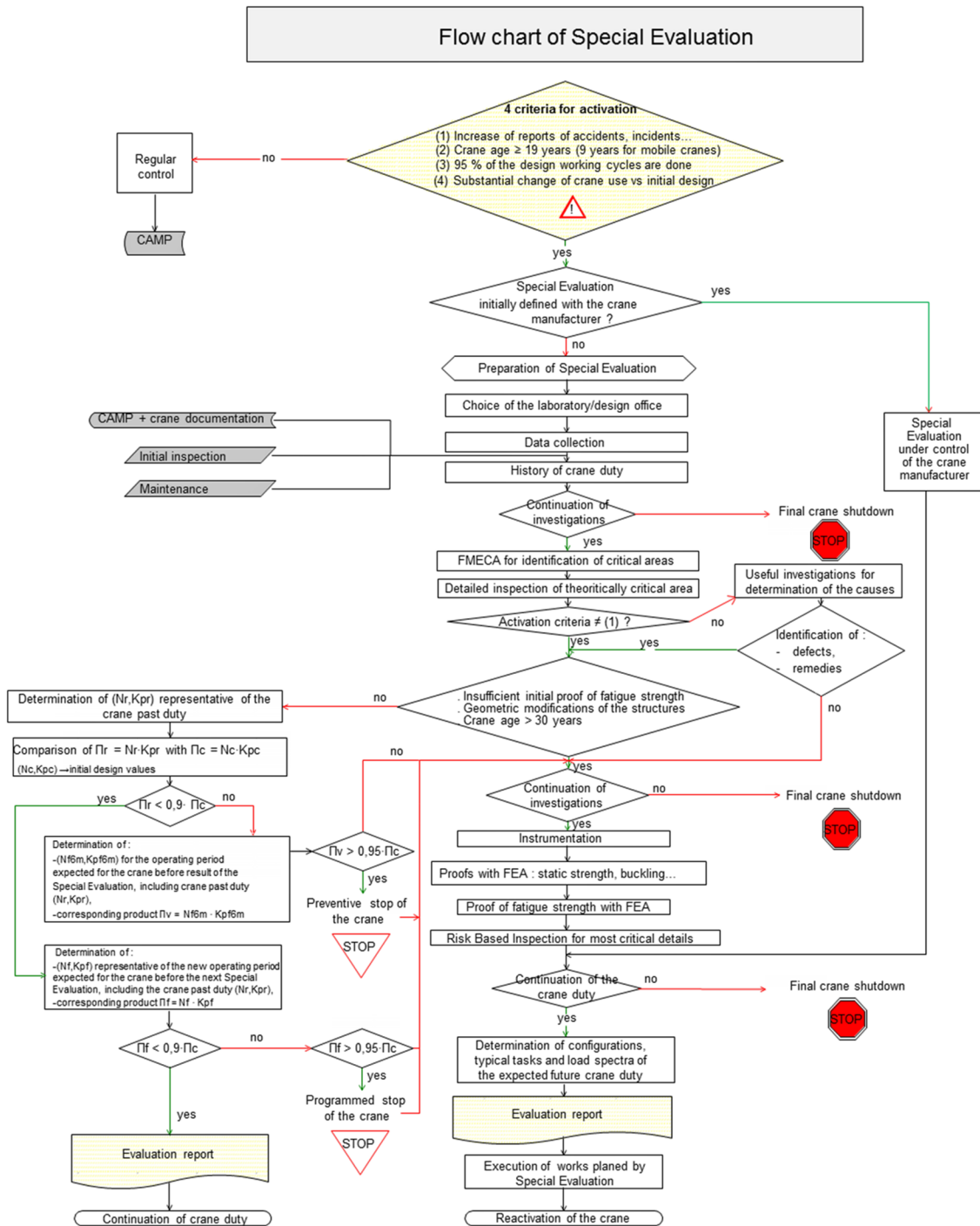


Fig. 8. Flow chart of the Special Evaluation (CETMEF Recommendation).

After more than one year of work, the procedure described below was published at the beginning of 2003. The Recommendations also include guidance, comments and calculation examples.

#### 4.2.1.2 Special evaluation procedure

In this clause, we focus on the main steps of the procedure called “Special Evaluation” whose flow chart is illustrated in Figure 8.

The procedure of “Special Evaluation” (vertical central line of the flow chart) shall be *activated* for at least one of the following criteria (first diamond in flow chart):

- increase in reports of accidents/incidents/inspections resulting from significant damage of the crane,
- the crane is at least 19 years old (9 years for mobile cranes): see Section 4.2.3.1 below as background,
- when the initial classification of the crane is known and 95% of its working cycles have been completed,

- substantial modification of the use of the crane compared to the expected duty at initial design stage.

If the crane manufacturer is not in charge of the “Special Evaluation”, a *reconstitution of the history/duty* of the crane is done as the first phase. All useful information shall be collected, such as crane configurations, number of working cycles, load spectra, incidents/accidents, and modifications of the crane.

At this stage, it can be decided to take the crane out of service, for instance, for economic reasons.

Otherwise, critical areas of the crane shall be identified and inspected next.

If there is any doubt about the integrity of the structure or if the use of the crane has changed compared to original design assumptions, then the “*Special Evaluation*” shall be performed, consisting of:

- potential instrumentation of areas judged to be critical,
- modelling (e.g. FEA) and calculations in accordance to FEM 1.001 Rules, including proof of fatigue strength,
- final identification of the critical areas,
- application of a Risk Based Inspection for the most critical constructional details.

Then *requirements for the future duty of the crane* are developed by the design office, such as:

- parts to be replaced,
- parts to be repaired,
- parts to be inspected, with the relevant inspection period,
- duration until the next “Special Evaluation”, this period cannot be lower than 10 yr.

This phase should take into account the future crane configurations and load spectrum, in agreement with the crane owner.

A *quick procedure* is also possible (left-hand side of the flow chart), for rare cases where:

- past duty is in line with initial design,
- history of the crane is reliable,
- no incidents/accidents/cracks/deformations reported.

It uses a “fatigue indicator” factor  $\mathbf{II}_r$  which is the product of:

- the estimated number of working cycles  $\mathbf{N}_r$ ,
- the load spectrum factor  $\mathbf{k}_{pr}$  based on estimated past duty.

It allows to by-pass the “Special Evaluation”.

#### 4.2.1.3 Feedback from experience

Since 2003, the CETMEF Recommendations have been used widely by the design offices in charge of assessments of old cranes.

This represents more than 500 studies and the procedure itself has proved to be practical and useful.

However, we have to add that the procedure has not mentioned explicitly the help of fracture mechanics in case of structures containing cracks.

#### 4.2.2 Ministerial Decree for old cranes (Italy, 2011)

In Italy, a Ministerial Decree of 11th of April 2011 established that cranes older than 20 yr should be submitted to an extra assessment of the structure the

purposes of which is to:

- identify potential cracks, defects or anomalies;
- determine their residual life and compare it to the original classification provided by the crane manufacturers.

The change introduced by this Decree is that such request for extra inspection should be addressed by the crane owner to the person in charge of the periodic inspections. Consequently, when a crane is 20 yr old, the owner is expected to ask the Expert Engineer to carry out the assessment of the structure.

We can see that, in Italy, even if this decree has not resulted in a specific methodology as in France for port cranes, the national authorities have decided on a special measure for old cranes, making the evaluation of their residual life mandatory.

#### 4.2.3 ISO 12482

##### 4.2.3.1 ISO 12482 monitoring for cranes (1995) [4]

The purpose of this 1995 ISO standard has been notably to define actions to be taken when a crane has been in service over a period of time, has approached the design constraints of the intended termination of its use and a new safe working period is to be ensured.

Requirements and responsibilities are given for a special assessment (SA, i.e. thorough examination and evaluation of the crane), in combination with inspections in accordance with ISO 9927-1 [6] and this special assessment should be carried out by an expert engineer. The Special Assessment report may include requirements for any action (GO, i.e. General Overhaul) to be taken before further use of the crane.

We have been told that when the crane user/owner does not have assessment criteria for a crane provided by the crane manufacturer, the special assessment SA (i.e. thorough examination and evaluation of the crane) shall be carried out not later than the following number of years after manufacture for:

- 10 yr for tower cranes, loader cranes, mobile cranes;
- 20 yr for all other cranes.

In the 1995 version, a detailed procedure was given only for serial hoist mechanisms, in Normative Annex A.

##### 4.2.3.2 ISO 12482 cranes – monitoring for crane design working period (2014)

A revision of this ISO standard started in 2008 and was finalized in 2014 because it had been necessary to:

- take into account feedback about experience on application of the 1995 standard,
- extend it to the crane structures and to all types of mechanisms.

This revision was also influenced by the content of the CETMEF Technical Guide.

The 2014 version has added the notion of Design Working Period (DWP) which is the operation period in a specific actual duty, within which the design duty is reached.

**Table 3.** Safety factor  $f_1$  for duty counting (ISO 12482:2014).

$N^\circ$	Method of duty recording	$f_1$
1	Automatic recording system, 4.2 a), or Counters and manual documentation, 4.2 b)	1,0
2	Estimation based upon a special, documented process, 4.2 c)	1,1
3	Estimation based upon documented production of the crane site, 4.2 d)	1,2
4	Estimation based upon undocumented, estimated production of the crane site, 4.2 e)	1,3
5	Crane duty history is unknown, 4.2 f)	1,5

The current version of the standard gives recommendations about records of the crane and it also gives methods for estimating the crane duty history; this estimation is divided into six categories depending on the reliability of the information and the estimated duty from the history shall be increased by a safety factor  $f_1$  to cover the unreliability in the duty recording and estimation (see [Tab. 3](#)).

The DWP (Design Working Period) calculation in ISO 12482 covers crane both as a whole, its structure and its mechanisms. The collection of the data on the use of the crane and the assessment of DWP should be linked to periodic inspections in accordance with ISO 9927-1 at 12 months intervals.

When initial classification and design are based on old standards, the re-calculation may be done with the applicable crane standards.

ISO 12482 provides two normative annexes giving examples of DWP calculations for cranes and hoisting mechanisms in accordance to ISO 4301:1986, in which classification rules are similar to FEM 1.001 ones (see [Sect. 4.1.1](#)).

### 4.3 Special assessment (SA)

A SA shall be made to survey the condition of the crane, when the assessment of DWP indicates that the crane duty will reach one of the design limits prior to the next periodic inspection, or at least one of the four activation criteria indicates that it should be done earlier. The first SA shall be performed no later than the specified operational lifetime of the crane or hoist as given by the manufacturer.

The SA shall be carried out by an expert engineer (see ISO 9927-1), it goes into more details and deals with critical components of the structure and of hoisting mechanisms of the crane. SA shall contain both a theoretical part (analysis of each critical component based on actual duty) and a practical part (major inspection in accordance with ISO 9927-1).

Once it has reached the end of its design life, the crane may only be used after a general overhaul (GO), based on a SA.

ISO 12482 also specifies what the SA report shall contain, at minimum (e.g. criteria used, results of the DWP analysis, and requirements for action to be taken to permit further use of crane, etc.).

### 4.4 General overhaul (GO)

The GO is a set of repair, replacement and maintenance actions necessary for the further safe use of the crane. Some issues may require immediate action; some may be postponed, in which case these actions must be scheduled according to the actual and future use of the crane. This distinction is illustrated by categories A, B and C in [Figure 9](#).

The following categories of actions can be identified:

- the component in which replacement may be necessary is always replaced in a GO, even though no physical evidence of damage is detectable;
- the component can be repaired, and possibly some parts only replaced;
- replacement of the component is uneconomical, in which case at the first GO a full inspection is carried out and an increased frequency of inspections and rejection criteria are specified for the future.

ISO 12482 also indicates what the responsibilities of crane user/owner are and it deals with manufacturer's instructions.

The crane owner is responsible for carrying out the periodic DWP assessments and for initiating SA with possible consequent actions, including a general overhaul (GO). He shall include the SA reports with the crane service documents and inform the expert engineer carrying out the SA about any past modifications of the crane.

The manufacturer shall provide the owner with the classification data necessary for the DWP assessment.

In Europe, there is no similar EN standard dealing with residual life of cranes, so ISO 12482 is referenced by some product standards, e.g. EN 15011 for bridge and gantry cranes or EN 14492 for hoists.

#### 4.4.1 Method for assessment of the remaining fatigue life of steel structures of existing STS cranes (2016)

This approach has been developed in an MSc thesis, establishing Lifetime Prediction, Inspection Intervals and After-Inspection Procedures for Ship-To-Shore (STS) cranes [10].

At first, it successively presents different standards on Fatigue Life Assessment dealing with cranes, bridges, offshore structures and aircraft (see also information in [16]).

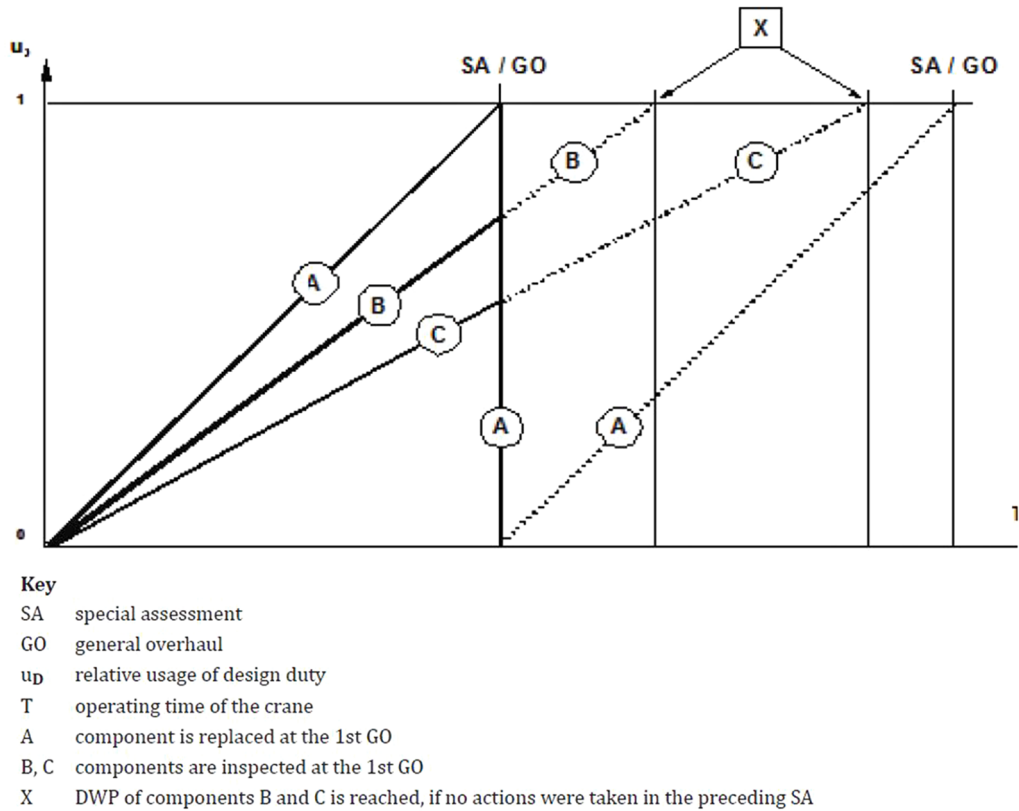


Fig. 9. Usage of design duty in relation to General Overhauls (GOs) and Special Assessments (SAs) in ISO 12482:2014.

Then, different fatigue failure modes are described for base material, welded connections, bolted connections and pinned connections.

The fatigue cracks are addressed in chapters dealing with:

- crack growth calculations (linear and non-linear methods),
- the measurement of crack sizes,
- repair methods for cracks.

Tools and flow charts are given for implementation of a model which calculates the remaining life of steel structures of existing STS cranes.

At final, a Fatigue Life Assessment method is provided, referencing EN 13001-3-1 [8] and this method is applied to a crane, using FEM software.

## 5 CETIM's (French Technical Institute for Mechanical Industry) general methodology for evaluation of residual life

### 5.1 Our feedback based on experience

CETIM is composed of many divisions (e.g. Simulation, Fatigue of Mechanical Components, Failure Analysis....) that have regularly to deal with evaluation of residual life or extension of service lifetime for a wide range of equipment, such as ski lift towers or autoclave with cracks, as illustrated in Figure 10.



Fig. 10. Examples of verified existing equipment.

The evaluation of some of those structures or equipment can be done with specific rules or standards, such as those mentioned previously, but for many others no procedure exists.

Consequently, over many years, a CETIM Working Group composed of engineers belonging to different divisions has developed an in-house methodology, using material from CETMEF Recommendations [9] and the JRC report [1].

### 5.2 CETIM's methodology

CETIM's methodology can be divided into six phases and its flowchart is shown in Figure 11 with the details of each step/phase given below:

- **Phase 1:** Preliminary evaluation;
- **Phase 2:** Assessment of load cases (*optional*);

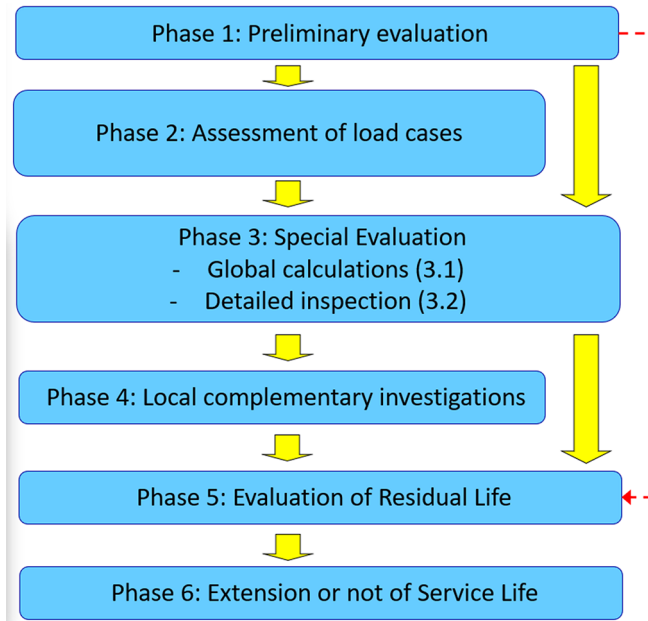


Fig. 11. Flow chart, CETIM methodology.

- **Phase 3:** Special Evaluation – 3.1 Global calculation and 3.2 Detailed Inspection;
- **Phase 4:** Local complementary investigations (*optional*);
- **Phase 5:** Evaluation of Residual Life;
- **Phase 6:** Extension or not of Service life.

### 5.3 Problems

Our long experience in estimating residual life has resulted in general comments that we have reported below, for each phase of the method.

A preliminary clear-cut agreement between all parties participating in the project (equipment owner, consultant(s), certification body...) is necessary before a start.

- **Phase 1:** Preliminary evaluation

For old equipment/structures, supporting documentation is often nonexistent, partial or based on obsolete standards that did not use accurate methods to deal with fatigue, so this assessment may be like sailing in uncharted waters.

During the inspection of an equipment, the good approach is *to look for the unexpected*, such as:

- corrosion due to neglected maintenance,
- fabrication shortcomings (e.g. full penetration welds executed with partial penetration, remaining welds of temporary supports, scars...);
- shortcomings arising from crane erection,
- unauthorized interventions: welds or drilled holes located in stress sensitive areas, often not registered,
- missing bolts,
- lower quality of bolts, etc.

For any major equipment, a preliminary inspection is de facto mandatory and a comparison of its findings with the original drawings if they are available, for future modelling.

The owner of equipment has also to ensure that the equipment is available for a sufficient time to allow a rigorous inspection.

- **Phase 2:** Assessment of load cases (*optional*)

In many cases, the loads and cycles applied to the equipment under consideration have not been reported/counted. If the equipment is very old, operators and technical staff from the initial period of service may have retired and it may be necessary to call them for a meeting.

In order to establish the load spectra of the equipment, it is sometimes necessary to train the crane owner staff to the basis of fatigue design (Wöhler curve, Miner's rule): this will facilitate the dialogue with engineers leading the assessment. An ISO standard such as ISO 9374-1 "Information to be provided" [11] can be useful during that phase.

- **Phase 3:** Special evaluation

#### 3.1: Global calculations

The fatigue strength of constructional details may be decreased compared to their theoretical values from standards when the quality of execution has been reported as low from the inspection.

- **Phase 3:** Special evaluation

#### 3.2: Detailed inspection of structure/equipment;

This phase completes phase 1 Inspection, it is more detailed and focused on identified concentration stress areas. It is usually visual but it can be completed using NDT methods.

The main purpose is identifying fatigue phenomena related to the past duty. Consequently, control methods are more often surface methods such as:

- magnetic particle testing,
- alternating current field measurement,
- eddy current,
- ultrasonic testing (UT) method (for specific points),
- investigative methods for bolted connections (for checking tightening torque), etc.

- **Phase 4:** Complementary local investigations (*optional*)

When the design fatigue life of equipment has expired or when cracks have been detected, it is necessary to calculate the remaining life using the fracture mechanics methods, which is not yet routinely mastered by many engineers in industry.

Only this technique will result in reliable inspection intervals provided to the equipment owner (see example in [2]).

- **Phase 5:** Evaluation of residual life

Whilst there are many engineers practicing Finite Element Analysis not so many are able to execute correctly a proof of fatigue strength. This is more critical in residual life estimation because the fatigue proofs in many standards are for design purpose only, and not appropriate when it is necessary to deal with residual life and consumed life.

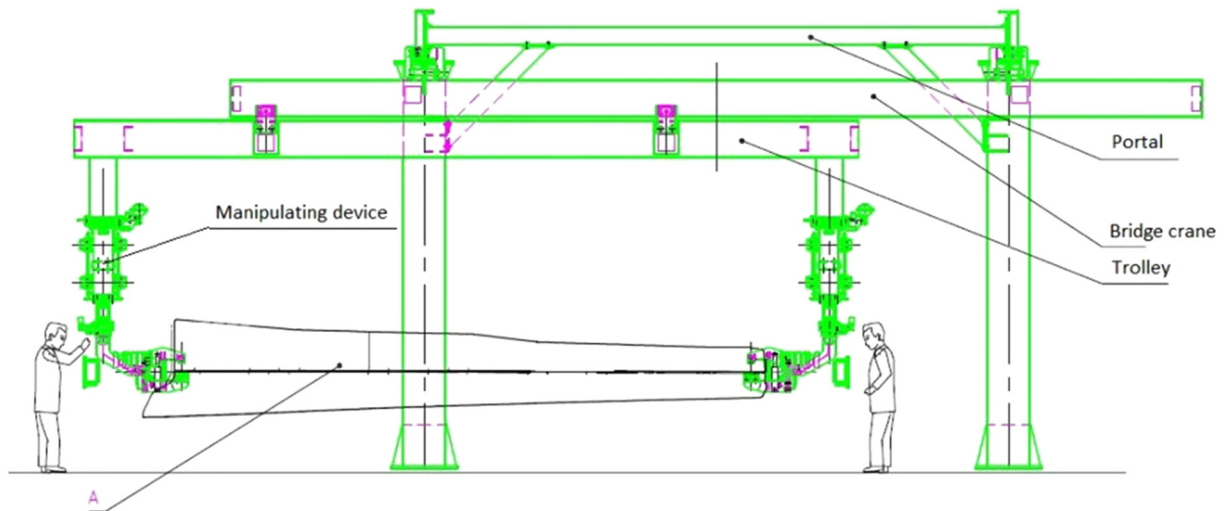


Fig. 12. Load manipulating devices (principle) with long manipulated part A.

In that step, it may be necessary to deal with risk acceptance criteria.

– **Phase 6:** Extension or not of Service life

Pragmatism is the keyword for this phase, because if the assessment of equipment results in the extension of service lifetime instead of its service being terminated, it may be a combination of:

- repairs,
- proposal of inspection plan, with local focus on critical areas that can have different inspection periods (which will be adapted by site feedback),
- installation of cycles counters (black boxes) or strain gauges (usage monitoring),
- declassification/derating (decrease of the rated load for a crane, for example), etc.

## 6 An example for cranes: load manipulating devices for AIRBUS

The purpose of the study has been to estimate the residual life of manipulating devices for AIRBUS A330 components (Nantes-Bouguenais, France). The manipulating devices consist of articulated components installed on a trolley with a travelling motion on a bridge crane, which itself is travelling on a fixed portal frame (see Fig. 12).

They were installed in 1999 and the desire of AIRBUS has been to keep them in service until 2027, in order to support the A330 program.

During **Phase 1** (Preliminary evaluation) load spectra have been established from the production records on industrial site, geometric configurations and working cycles of the devices have been determined thanks to a close collaboration with the operators. Initial calculation reports have been studied and notably the assumptions made in the original proof of fatigue strength.

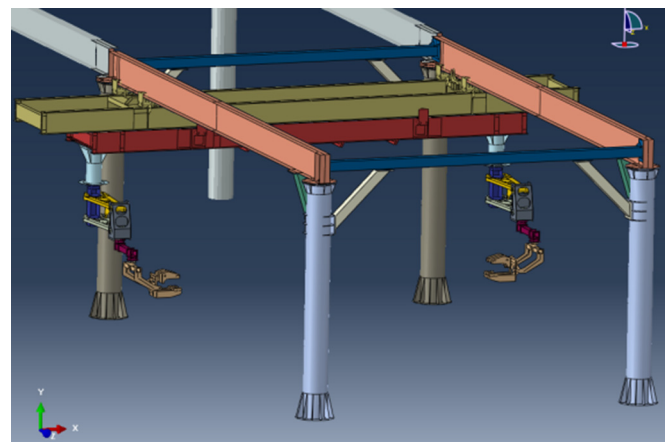


Fig. 13. Load manipulating devices, model file.

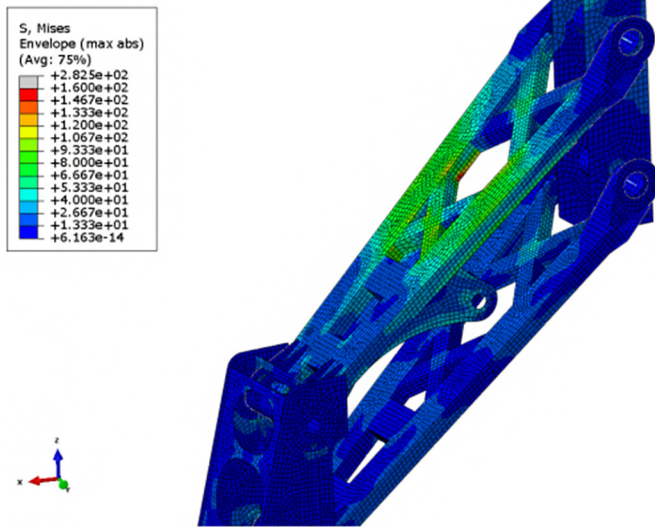
During **Phase 2** (Assessment of load cases) new load combinations have been prepared, based on FEM 1.001 because it was the reference for original design.

Finite Element Analyses (FEA) have been performed during **Phase 3.1** (Global calculations, see model file in Fig. 13) and some stress concentration areas have been identified, e.g. in the arm of the manipulating device (Fig. 14).

During **Phase 3.2** (Detailed inspection of structure/equipment) after its complete visual inspection (of structure and mechanisms) the equipment has been reported as globally healthy and with very few defects.

The **Phase 4** (Complementary local investigations) was not required in the present case with no fatigue cracking or defects identified on the structures during our detailed inspection, in the previous **Phase 3.2**.

At final, the evaluation of residual life (**Phase 5**) was done using the factor  $f_1$  from ISO 12482 (see Tab. 3) for a scenario 2017–2027.



**Fig. 14.** A typical map of von Mises stresses, in an arm, for one load combination.

**Phase 6** (Service life extension) as a result of the assessment, service life extension has been granted with no repairs required and inspection periods defined and taking into account fatigue damages of different members of the supporting structure, bridge crane, trolley or manipulating devices.

## 7 Conclusion

The evaluation of the residual life of structures and equipment has been progressively dealt with an increasing number of references. But the documentation is still limited compared to the size and complexity of the problem.

All the existing methods are based on several steps that have to be carried out in sequence.

A good evaluation of residual life requires at least a combination of expertise in inspection, NDT, engineering analysis often including Finite Element Analysis and a good familiarity with fatigue calculations. The techniques of fracture mechanics are required more and more, and knowledge of applied reliability is another plus.

CETIM has progressively developed its own methodology of assessment of existing equipment/structures and this has been briefly described, together with its application to an AIRBUS load manipulating device.

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## References

- [1] JRC43401, Assessment of existing steel structures: recommendations for estimation of remaining fatigue life – background documents in support to the implementation, harmonization and further development of the Eurocodes, joint report, EUR 23252 EN – 2008
- [2] Y. Chen, Y. Sun, Study of residual life prediction and maintenance decision-making of portal crane, International Technology and Innovation Conference, 2009 (ITIC 2009)
- [3] A. Hobbacher, Recommendations for fatigue design of welded joints and components; IIW-1823-07/XIII-2151r4-07/XV-1254r4-07, 2008
- [4] ISO 12482, Cranes — Monitoring for crane design working period
- [5] Eurocode 3: Design of steel structures – Part 1-9: Fatigue, 2005
- [6] ISO 9927-1, Cranes – Inspections – Part 1: general
- [7] FEM 1.001:1998, Rules for the design of hoisting appliances (3rd edn.)
- [8] EN 13001-3-1:2018, Cranes – General Design – Part 3-1: Limit States and proof competence of steel structures
- [9] Recommandations applicables aux appareils de levage “anciens” dans les ports, Guide Technique, CETMEF, PM 03.01, Novembre 2003
- [10] J.A. van Hole, Development of a method for assessment of the remaining fatigue life of steel structures of existing STS cranes, M. Sc. Thesis, 2016
- [11] ISO 9374, Cranes – Information to be provided (series of standard)
- [12] DIN 15018-1:1984, Cranes – Principles for steel structures, stress analysis
- [13] D.T. Hai, Current status of existing railway bridges in Vietnam: An overview of steel deficiencies, J. Constr. Steel Res. **32**, 987–994 (2006)
- [14] I. Imran, D. Hoedajanto, I. Zarkasi, Bridges in Indonesia, Present and future, International Forum, JSCE Century Anniversary, Tokyo, 2014
- [15] M.M. Hassan, S.A. Elswaf, H.H. Abbas, Existing metallic bridges in Egypt: current conditions and problems, J. Civil Struct. Health Monit. **7**, 669–687 (2017)
- [16] Practical Structural Examination of Container Handling Cranes in Ports and Terminals, A PEMA IP09 Information Paper

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