Fatigue Assessment of Structures Using FEA and Advanced Methods

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Hello. Good Morning.

Lets start by providing the PDH code for this presentation, which is 26128. I repeat, 26128.

So, starting things off with the introduction of ourselves.

We are both structural engineers at EMASA Engineering, a small specialized office focused on erection engineering and advanced structural analyses, with formal presence both in the Netherlands and in Brazil.

Our portfolio includes a wide range of projects, such as: petrochemical and industrial plants, stadium roof structures, gridshells and bridges. Those are often developed in an international context across Europe, the Americas, and Africa.

We work closely with general contractors, fabricators, and erectors. Mostly by providing support to other engineering firms for complex structural problems, involving:

- Staged construction analyses for erection,
- highly non-linear elements, such as cables,
- complex dynamic behaviour, such as time history analyses for wave and earthquake loads,
- And details requiring advanced finite element analyses

In recent years, a significant part of our work has been dedicated to the design of offshore structures, particularly for wind farms in the North and Baltic Seas.

We work on the design of structures both for the generators, as seen on the left and the substations, as seen on the right.

These structures are highly fatigue-driven, which has given us extensive practical experience with different fatigue analysis methods, from direct code-based approaches to more advanced techniques, with heavy use of finite element analyses.

Today, we would like to share some of that experience with you, focusing on how advanced fatigue analysis is treated in practice.

The goal of this presentation is to provide you with an understanding of the theory behind the advanced fatigue assessment techniques used in the offshore design.

This talk is aimed at the competent structural analyst who does not deal with fatigue on a daily basis, but who wants to become more familiar with the topic.

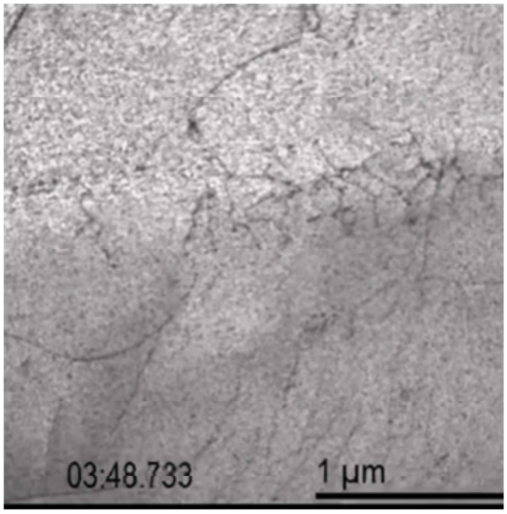
And also, to the engineer who has performed fatigue checks in simpler cases but wants to understand how those extend to more complex situations.

This is not intended to be a deep theoretical treatment. We will not go, for example, into detailed crack growth derivations, material testing procedures, or complex mathematical formulations.

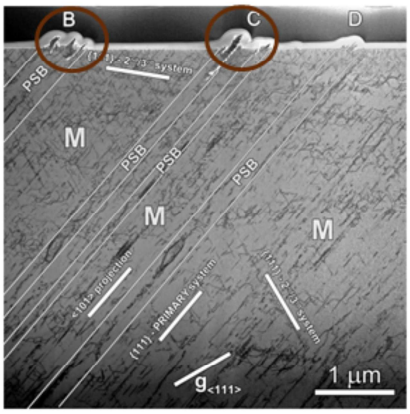
Instead, the focus is on giving you a clear usable mindset related to fatigue analysis, that you can apply in real engineering situations.

Fatigue Mechanisms
Crack Initiation

MOVING DISLOCATIONS



PERSISTANT SLIP BANDS ➔ CRACKS



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So let's start from the basics— how fatigue develops.

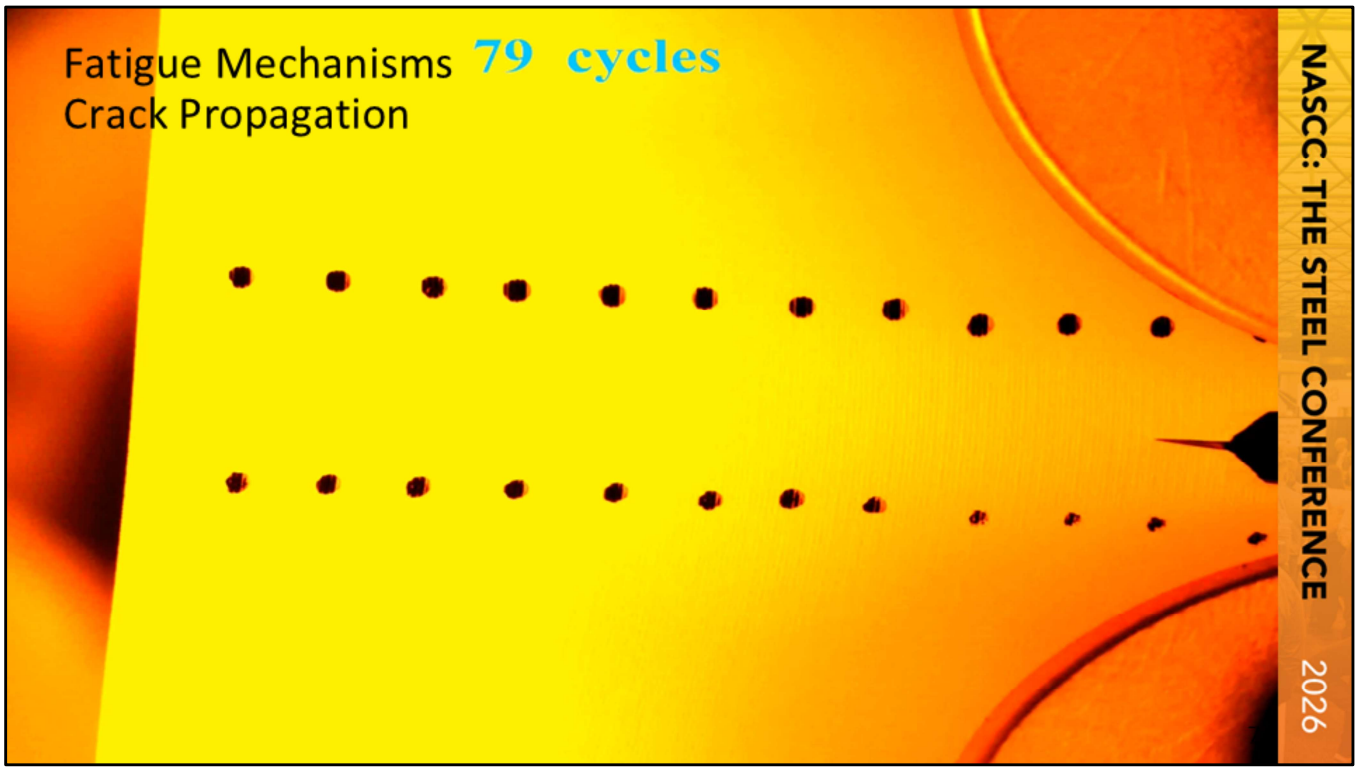
Fatigue failure in a material typically develops in two main phases: crack initiation and crack propagation.

The initiation phase starts long before any visible crack exists. It is related to the microscale plasticity within the material.

The clyclic loading leads to the accumulation of the existing microscale dislocations into the so-called persistent slip bands, inducing with this the appearance of cracks.

For fatigue design in practice, we are not much interested in this phase, because it only has a meaningful life duration for materials with a smooth surface.

For most real life structrues, we can assume that the steel is never perfectly smooth, with cracks being already present from the beginning of the lifetime, especially for welded details.



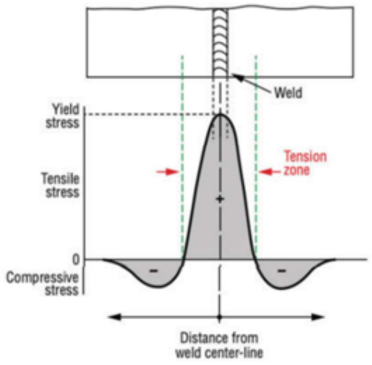
So, the next phase of fatigue development, the crack propagation, is often assumed to be immediate, with most of the material fatigue life spent in it.

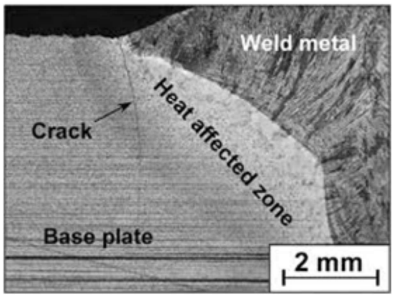
At the propagation phase, the crack begins to grow incrementally with each load cycle.

Initially, the growth is slow and stable, but as the crack increases in size, the growth rate accelerates.

This short video illustrates the propagation process.

Role of compressive forces and heat affected zone





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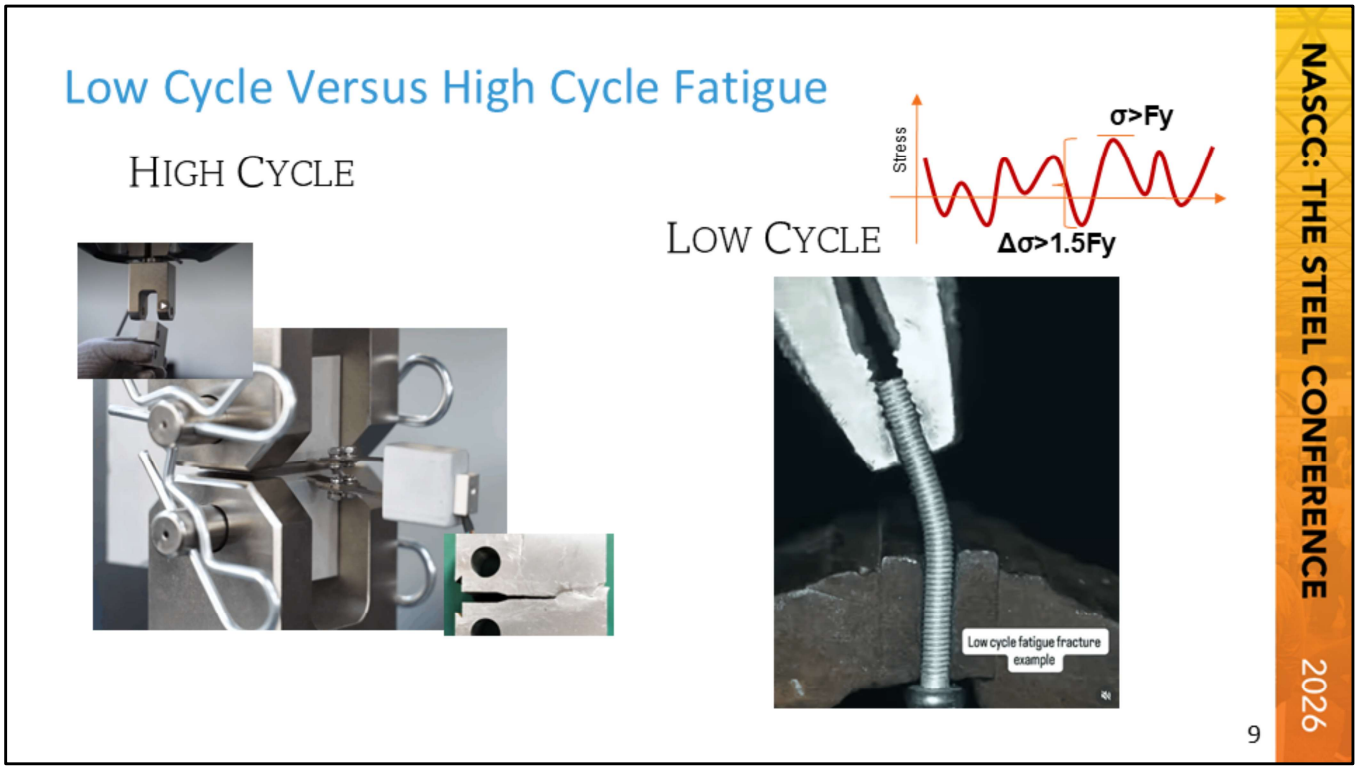
Fatigue crack growth is most associated with tensile stresses.

Obviously, a crack can only open and propagate when the stress at its tip is tensile, because crack growth requires separation of material along the crack faces. Under pure compression loading, the crack faces are pressed together, which tends to inhibit propagation.

However, this does not necessarily mean that fatigue is negligible for details in compression. In welded joints, the heat affected zone, often remains in a state of tensile residual stress, even if the external loading is compressive.

This means that, at the local level, the material can still experience cycles of stresses in tension, allowing cracks to initiate and propagate locally even in members that are globally in compression.

We will discuss this aspect some more in the section where we compare the approaches from the structural codes, since AISC and the Eurocodes see this effect from different perspectives.



When we talk about fatigue, it is also very important to distinguish between what we call high-cycle fatigue and low-cycle fatigue.

This terminology can be a confusing at first, but it simply reflects how high are the number of cycles associated with failure and, more importantly, the type of material behavior involved.

High-cycle fatigue refers to situations where the number of cycles being considered in the analysis is very large—typically in the order of hundreds of thousands to millions of cycles—and the stresses remain mostly within the elastic range of the material. This is the regime that most structural steel design is based on.

In this case, even though the stresses are relatively low, the high number of repetitions is what drives the damage. From a design perspective, this is where we want our structures to operate, because the behavior is more predictable and can be assessed using linear elastic analysis.

On the other hand, low-cycle fatigue occurs when the number of cycles is relatively small, but the stress levels are high enough to cause significant plastic deformation in each cycle. Here, the material is no longer behaving elastically, and fatigue damage is governed by cyclic strains rather than stresses.

The transition from one regime to the other is characterized by the presence or not of cyclic plasticity.

Some codes give a very practical criterion for this: the standard fatigue high cycle design approach is not applicable anymore when the stress range exceeds 1.5 times the yield strength. Or, also, when the maximum stress exceeds the yield limit.

From a practical engineering standpoint, low-cycle fatigue is not something we typically aim to design for in standard structural applications. It is more commonly associated with extreme or accidental loading conditions, such as seismic events, or with fitness-for-service evaluations where damage has already developed.

Now comes the question: When do we actually need to check for fatigue?

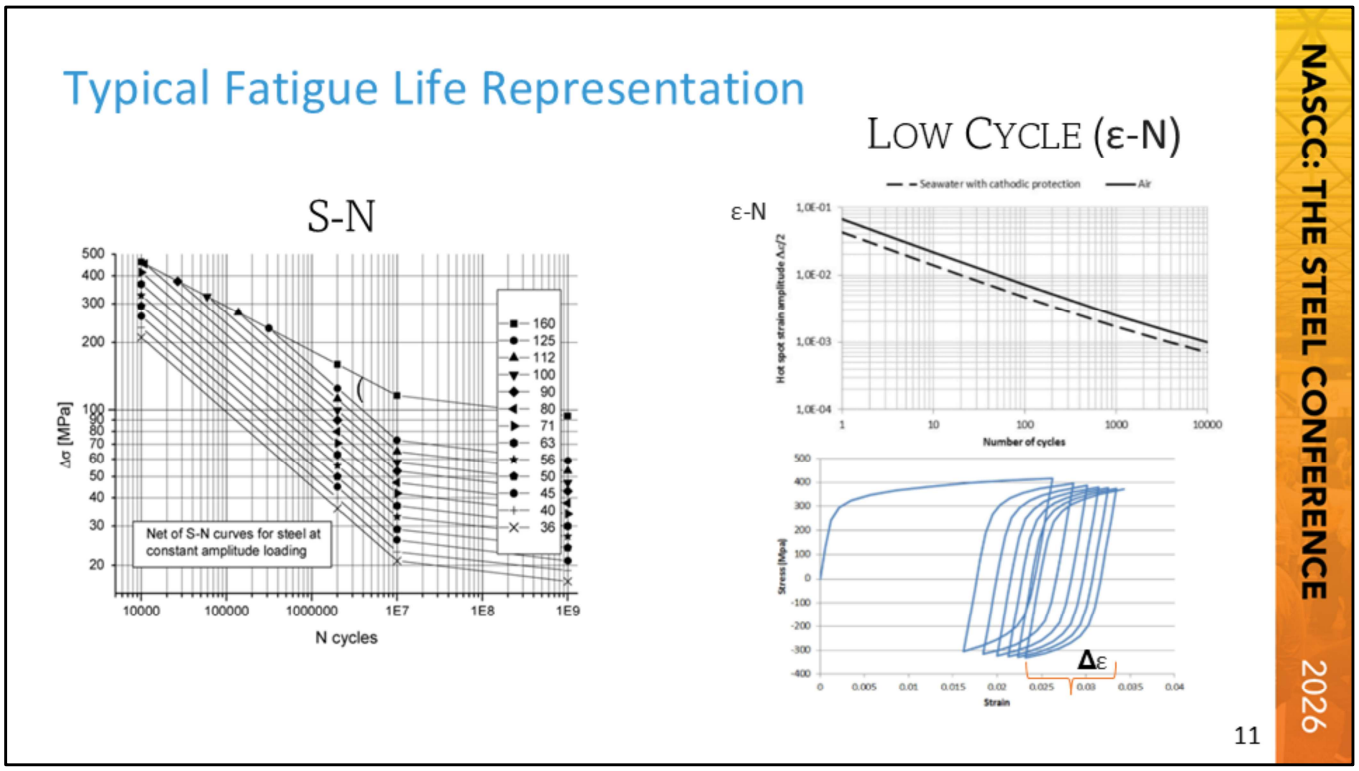
Some cases are clearly fatigue-driven, such as offshore structures subjected to wave loading, cranes with repeated lifting operations, industrial facilities with rotating equipment, or bridges under traffic.

But there are also less obvious situations where fatigue can become critical, particularly in structures sensitive to dynamic effects.

For example, slender towers, with natural frequencies within the range of high excitations from wind turbulence, can experience a very high number of relevant stress cycles, even under relatively small loads.

Also, phenomena such as vortex shedding can further amplify these effects for some structures.

In summary, there is no single rule that tells us exactly when to check for fatigue, and engineering judgment becomes essential.



Now let's talk about how to represent the fatigue life in our calculations. The most common way is through the so-called S–N curves, with "S" for range of stresses and "N" for number of cycles. This is what most design codes are built on, and what most engineers are familiar with.

At first glance, the concept looks simple: for a given stress range, you can estimate how many cycles the structure can sustain before failure. But in reality, the correct use of S–N curves is quite nuanced and requires careful attention.

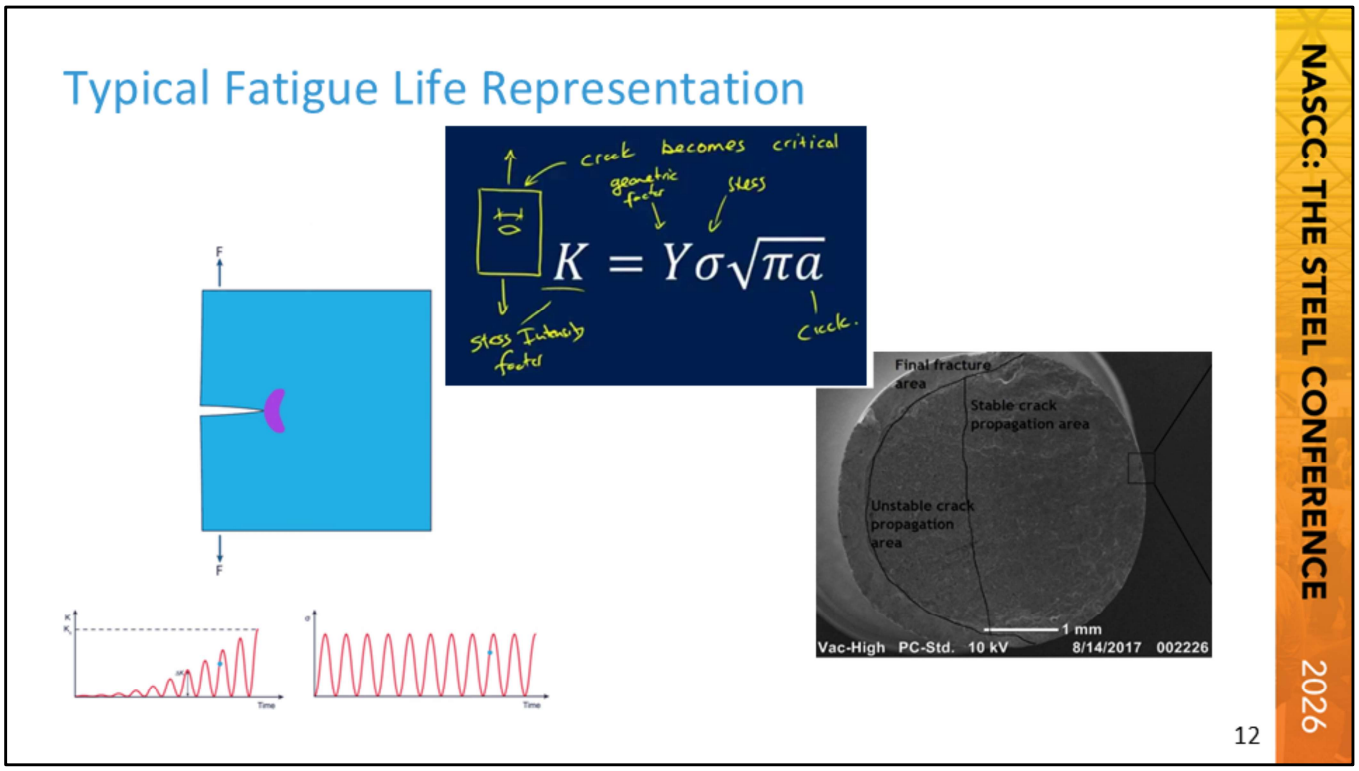
One of the key challenges is selecting the appropriate S–N curve for the specific problem. These curves are not universal—they depend strongly on the configuration of the structural detail. Also, the stress range to be used must be consistent with the purpose of the S–N curve. Mixing stress definitions and S–N curves is one of the most common sources of error in fatigue assessment.

In addition, factors such as mean stress effects, residual stresses, and the environment can influence how these curves should be applied.

Now, while S–N curves dominate most practical applications, they are not the only way to represent fatigue behavior.

For Low Cycle fatigue, epslon–N curves – with epslon meaning strain - are used instead. In this approach, the controlling parameter is no longer the stress range, but the cyclic strain range, including both elastic and plastic components.

This introduces additional complexity, because it requires us to capture cyclic plasticity accurately in the analysis. That means nonlinear material models, careful determination of the strain ranges, and attention to how hysteresis develops under repeated loading.



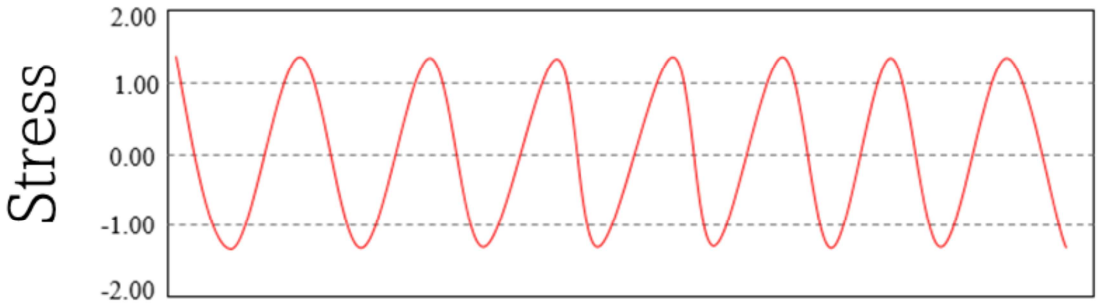
At a more fundamental level, fatigue life can also be represented in the framework of fracture mechanics. In this framework, we do not directly relate stress to life, but instead track the growth of a crack through the material.

The life of the component is then typically associated with two limits: a geometrical criterion related to the limiting acceptable dimension of a crack; and a material criterion, related to the condition when a crack becomes unstable and fails abruptly.

For the last, the key parameter is the stress intensity factor - a quantity that blends the stress values around a crack and the crack geometrical aspect. It characterizes the stress field at the crack tip.

As the crack grows, the stress intensity factor increases, and failure is assumed to occur when it reaches a critical value, usually the material toughness parameter.

Constant Amplitude Stress Cycles Analyses (13-14min)



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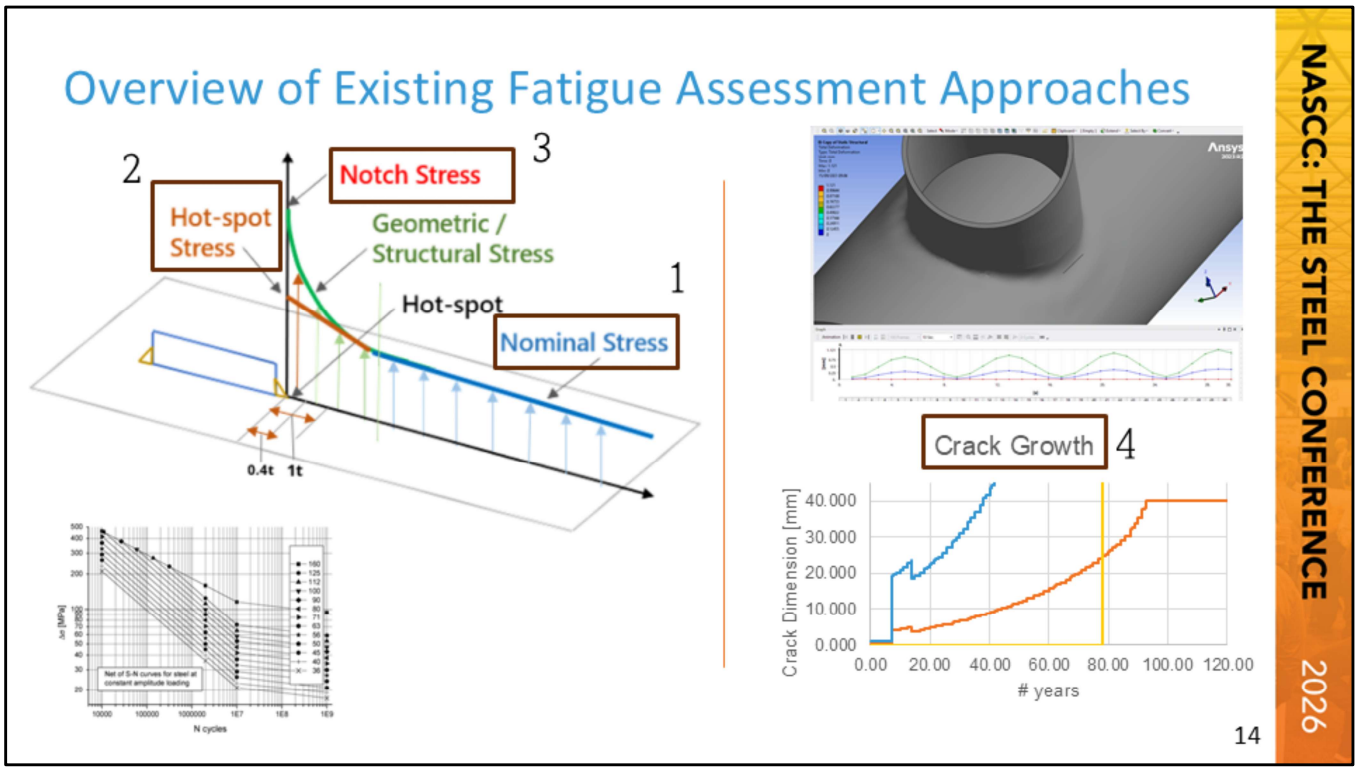
From this point on, we move into the more analysis focused part of the presentation, and for now we will assume a simplified scenario where the structure is subjected to constant amplitude stress cycles.

This is not how most real structures behave, but it provides a clean starting point to understand the different fatigue assessment methods.



We will start this section with an overview of the theory-based available fatigue assessment methods.

The nomenclature we present here is the one used for the fatigue analysis theory from the International Institute of Welding, which bases most of the fatigue analysis in Europe.

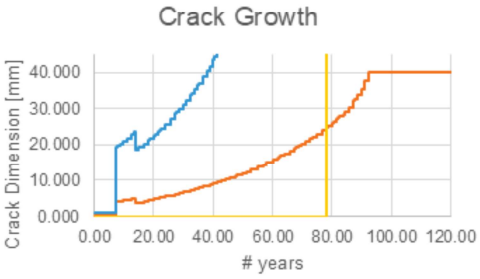
The key idea is that there is not a single way to evaluate fatigue. Several methods exist, each with a different level of refinement, required effort, and degree of conservatism.

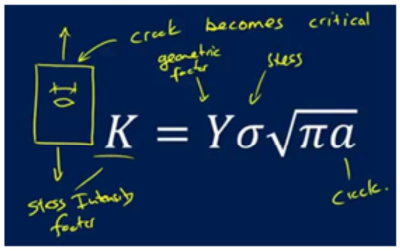
In general, we can say that 4 methods exist for the advanced fatigue checks in practice, with three of them being based on the S-N curves concept, each of them contemplating the stress raising effects in its own manner, and a fourth method based on fracture mechanics.

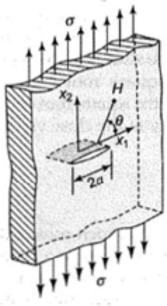
At one end, we have simpler approaches like the nominal stress method, which relies on predefined detail categories and is widely used in design codes. At the other end, we have more advanced approaches such as the effective notch stress method, and fracture mechanics, which attempt to capture the ultra-local behavior very accurately.

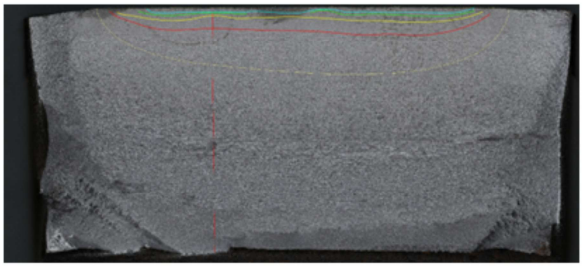
As we move toward more refined methods, the analysis becomes more detailed and less conservative, but also more demanding in terms of modelling and interpretation.

Fracture Mechanics Approach









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Starting with the most complex method…

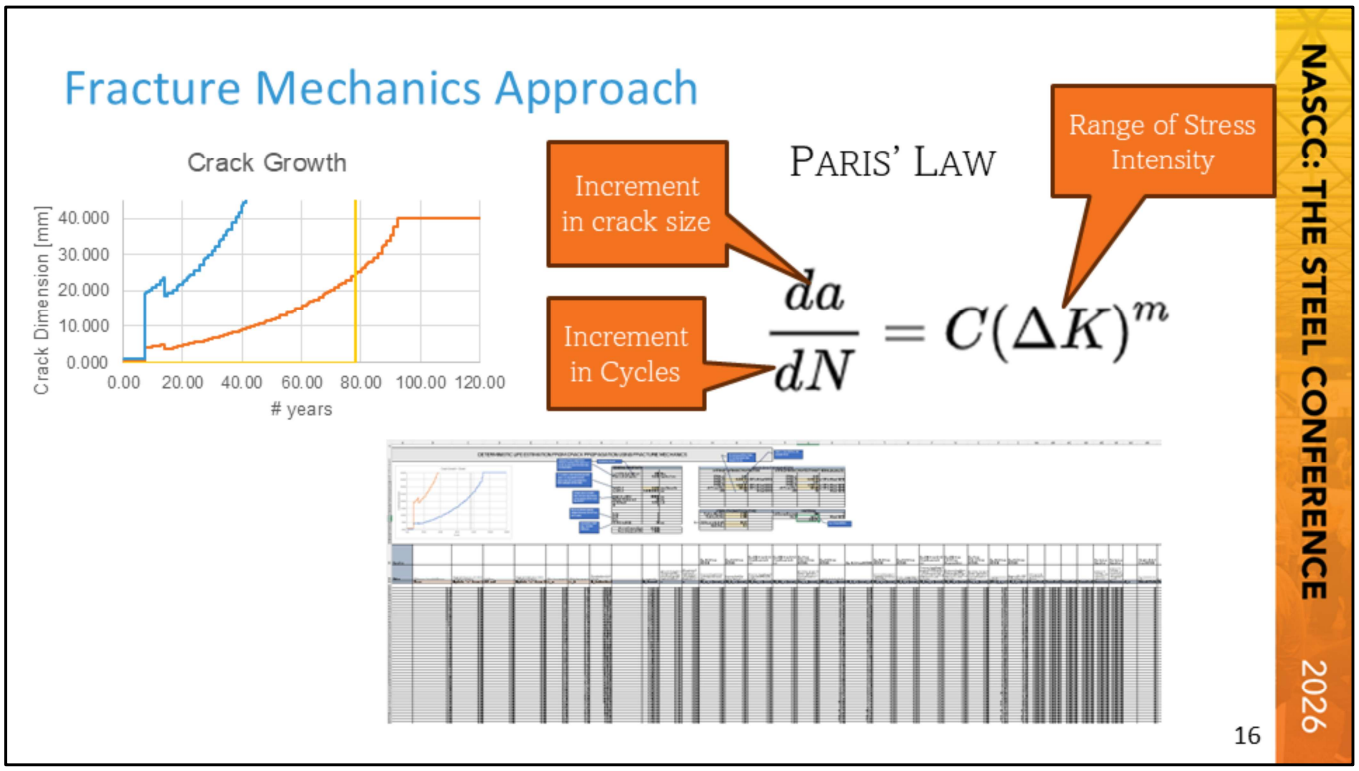
The most theory-driven approach to fatigue assessment is fracture mechanics, and it is conceptually quite different from the S–N based methods.

Instead of relating a stress range directly to a number of cycles to failure, fracture mechanics starts from the assumption that a crack already exists and focuses on how that crack propagates under cyclic loading.

In practical applications, the analysis usually starts by assuming an initial crack with a given size and geometry.

Typically an elliptical or semi-elliptical crack is assumed, although in real assessments the initial flaw can also be taken from inspection data.

As mentioned before, the stress intensity factor is the key parameter in this approach.



In fracture mechanics, the crack growth is evaluated through the Paris law, where the growth in a cycle is linked to the range of stress intensity factor within that cycle.

Although this may sound mathematically heavy because it involves integrating an equation, in practice it usually just means solving the problem incrementally in many small steps.

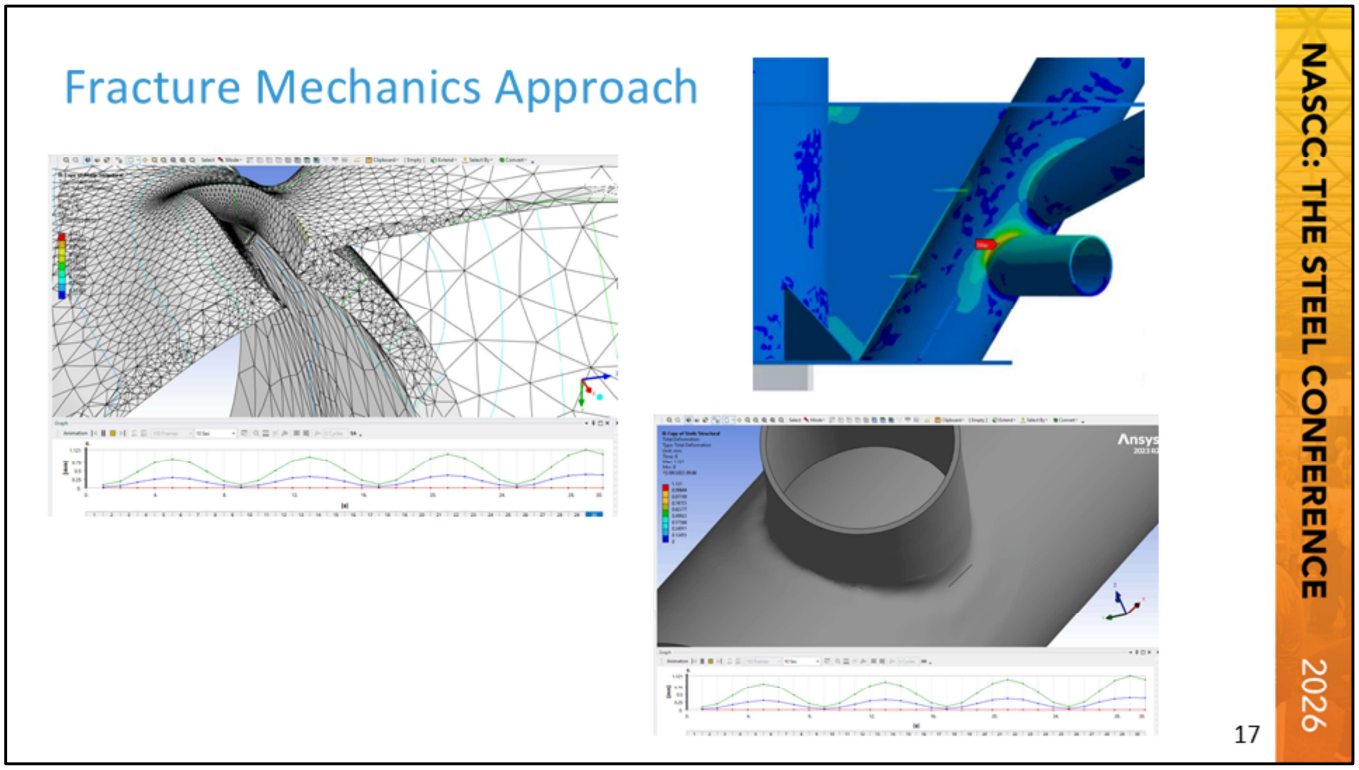
You can, for example, calculate the crack growth for an assumed small number of cycles; update the crack size; recalculate the stress intensity range; and repeat. It is often nothing more than a long and systematic table of repeated calculations.

One major strength of fracture mechanics is its flexibility. In principle, any steel detail or component can be analysed with this approach—bolts, welds, kinks, dimples, etc. That is because the method does not depend on having a predefined category from a code table. What it needs is the material parametrization, the geometry of the component, and a reasonable definition of the initial crack size and position.

This makes it especially powerful for unusual details, damaged components, or situations where code-based classification is unclear or not available.

That is why fracture mechanics is widely used in research. But also in fitness-for-service evaluations, and in the prediction of remaining life for structures where damage has already been detected.

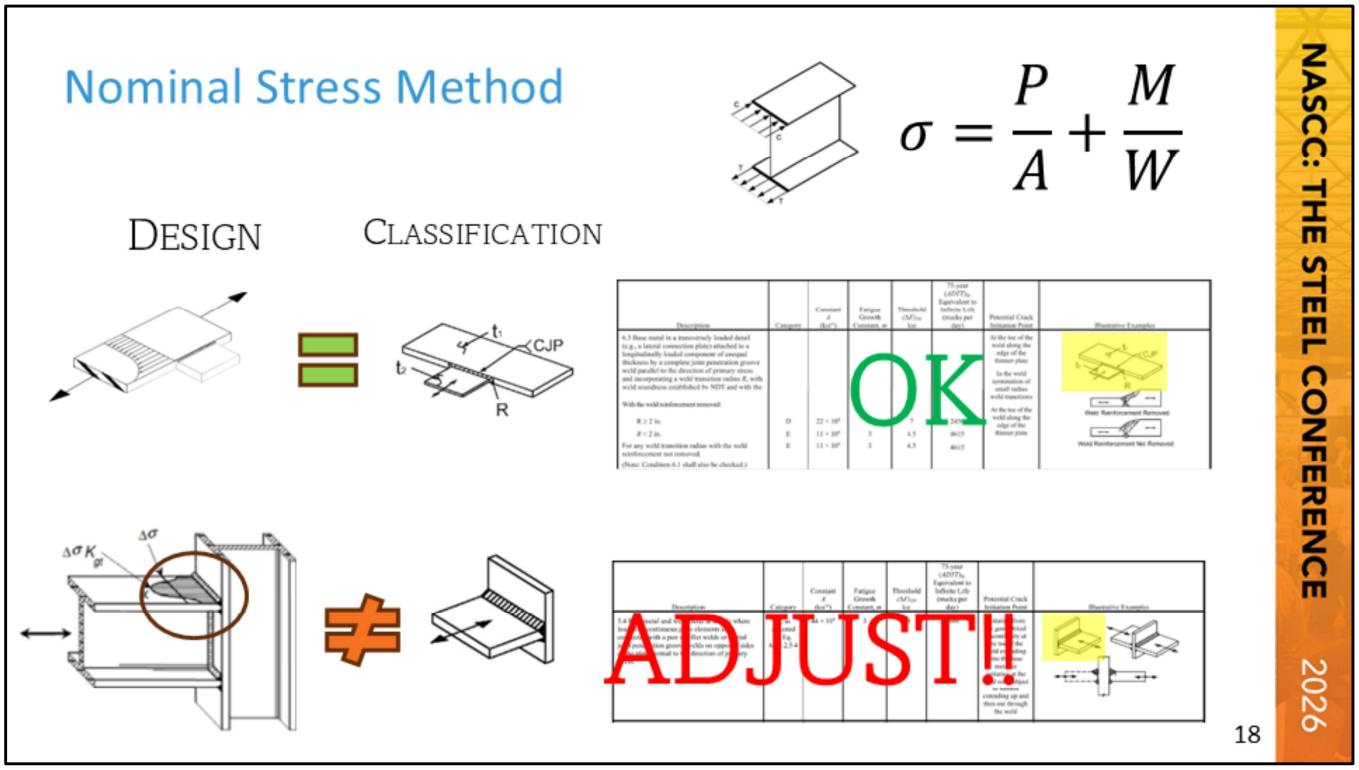
It is also very useful for inspection planning, because it allows engineers to estimate how long a crack will take to grow from a detectable size to a critical size.



Finite Element Analysis plays a very important role in this process. In simpler cases, analytical solutions for the stress intensity factor may be available, but for real structural details the geometry and stress field are often too complex for closed-form expressions.

In those cases, finite element analysis is used to capture the stress distribution in the detail and to provide the input needed for the crack growth evaluation.

In more advanced workflows, specialized tools can even simulate crack growth directly, updating the mesh at the crack front and the stress intensity factors automatically as the crack propagates.



Now we move into the S–N curve based methods, starting with the simplest and the most widely used in practice: What the theory calls the nominal stress method.

Before going into the method itself, it is important to clarify what we mean by “nominal stress”, because this term often brings confusion, especially in the US.

The term “Nominal stress” is used in the US to refer to the unfactored or service-level stresses. But in fatigue theory, nominal stress has a different and more specific meaning.

For the theory it refers to the far-field stress calculated using basic structural mechanics—such as, for a beam, P over A and M over W—without including local stress concentrations caused by geometric discontinuities or local load introduction effects. So, it is essentially the stress in the member assuming it behaves as a simple, idealized structural element.

The nominal stress method is based on classifying structural details into

predefined categories, each associated with a specific S–N curve. These categories already account, in an implicit way, for the typical stress direction changes and concentrations related to those specific details.

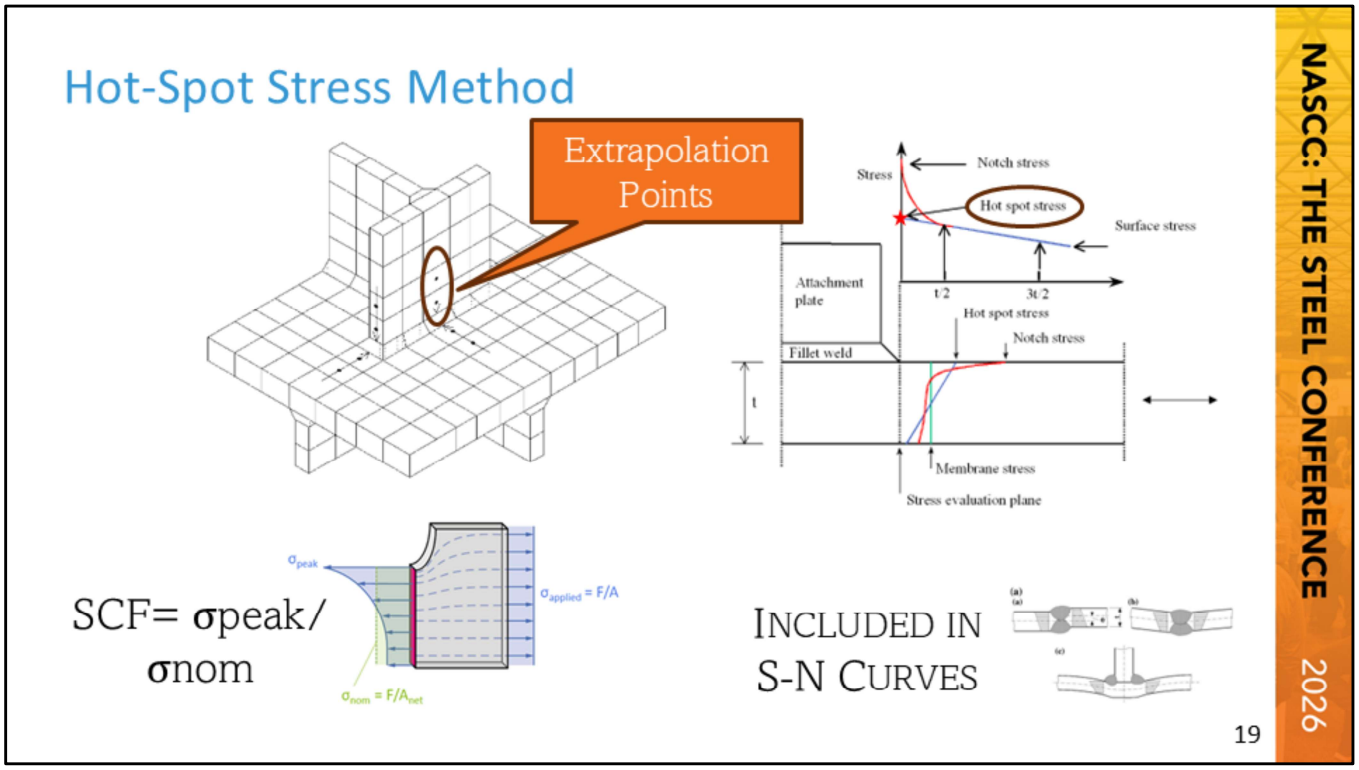
The method is mostly intended to avoid the need for detailed finite element analysis and is directly applicable to a wide range of common structural details encountered in practice. It is the backbone of most fatigue provisions in design codes, and therefore the method that most engineers rely on in everyday design.

However, this apparent simplicity hides one of the most common sources of error in fatigue assessments. The method is only directly applicable when the actual structural detail and loading condition *does not deviate* from the configuration of the classified detail in the code. In that case, the nominal stress calculated in the most simple manner can be used.

But, in many real situations, the geometry or the loading introduces additional stress concentrations that are not accounted for in the classification. When that happens, the nominal stress must be adjusted to include those effects. Using the unadjusted nominal stress in those cases can lead to unconservative results.

Also, on the other, hand including the stress concentrations that are already covered in the classification, lead to overconservative checks.

So, while the nominal stress method is simple, robust, and extremely useful, it requires a clear understanding of what “nominal stress” actually represents, when it can be used directly, and when it must be adjusted.



The next level of refinement beyond the nominal stress method is the hot-spot stress method, which is mainly used for welded details where the nominal stress is not well defined in the design tables.

This concept explicitly calculates the stress concentration factor, which represents how much the geometry amplifies the stress compared to the nominal far-field stress.

The idea of this method is to capture the stress increase caused by the overall geometry of the detail—such as attachments, or abrupt changes in stiffness—while excluding the local stress raising effect from the notch present at the weld.

The stresses are typically obtained from finite element analysis, but they are not taken directly at the weld toe. Instead, stresses are evaluated at specific distances away from the weld and then extrapolated to the weld location.

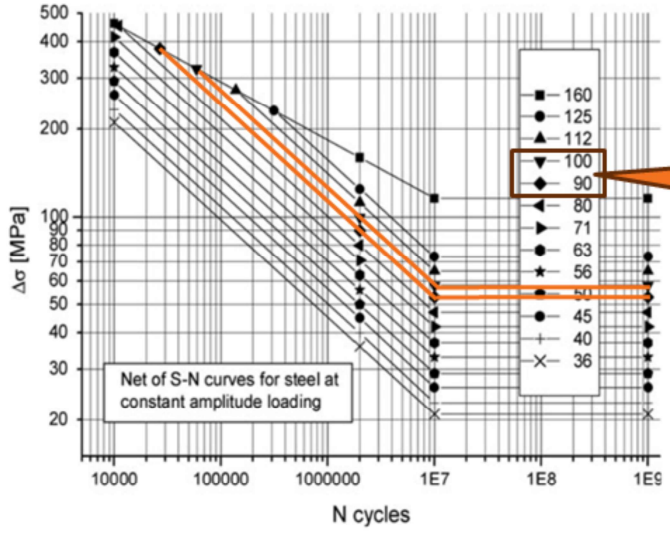
The reason for this is twofold. First, from a numerical standpoint, the weld toe represents a sharp geometric discontinuity, which leads to stress singularities in finite element models—meaning that the stress can increase indefinitely as the mesh is refined.

Second, even in analytical elasticity solutions, sharp notches lead to very high local stress gradients because the load path is forced to change direction abruptly.

By extrapolating from points away from the weld, we obtain the so called hot-spot stress that reflects the overall geometry-driven stress concentration, but is independent of mesh size and not dominated by the high stress gradient at the weld notch.

Hot-Spot Stress Method

CURVES FROM NOMINAL STRESS METHOD



Only a ***Subset*** is used for Hot-Spot Stress evaluation

No.	Structural detail	Description	Requirements	FAT Steel	FAT Alu.
2		Cruciform or T-joint with full penetration K-butt welds	K-butt welds, no lamellar tearing	100	40
6		Cruciform joints with load-carrying fillet welds	Fillet welds, as welded	90	36

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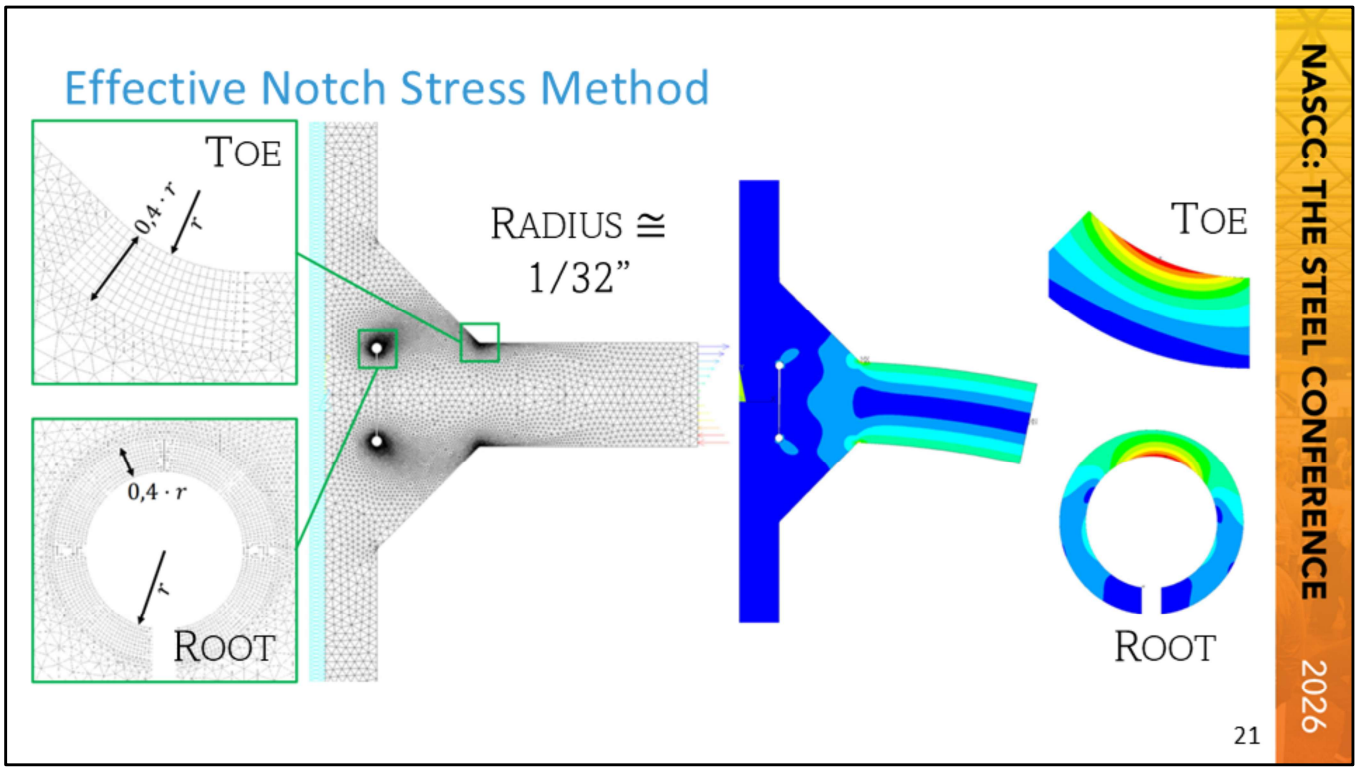
Even though this method reduces the dependence on detail classification compared to the nominal stress method, some classification is still required for the selection of the appropriate S–N curve.

This is because the method does not capture effects such as weld quality; weld profile; crack initiation location; and misalignments. These aspects are still contemplated in the values at the S-N curves.

So, for example, different S–N curves are used depending on:

- whether failure is expected at the weld toe or the weld root;
- whether the weld is a fillet weld or a full penetration weld;
- whether inspection is possible;
- and depending on environmental conditions: such as air versus seawater.

Overall, the hot-spot stress method provides a balanced approach. It captures the main structural stress concentrations explicitly, avoids the numerical issues associated with ultra local peak stresses, and allows for a more consistent treatment of complex welded details, while still remaining compatible with standard S–N based fatigue assessment procedures.



The next level of refinement in the theory is the Effective notch stress method, which focuses on the very local stress behaviour at the weld toe or root.

Unlike the hot-spot method, which excludes local notch effects, this approach explicitly *includes* them by modelling the weld geometry in detail.

To solve the numerical problem due to the singularity, a modelling standardization is made. Instead of using a sharp geometric discontinuity, the method introduces a small defined radius at the weld toe or root of 1mm, around 1 32nd of an inch.

This is what we call the “effective notch,” and it allows the calculation of a finite and standardized stress at that location for the analysis. The stresses are then taken directly at the face of this radius, without the need for extrapolation.

Because this method captures very local stress effects, it requires a very fine mesh and strict modelling rules to ensure consistency. The stress results are highly sensitive to mesh size, element type, and how the weld geometry is represented, so codes and recommendations provide the specific guidance, and those must be followed closely.

The curves for this method are calibrated for the modelling approach mentioned

above. And the fatigue assessment is then performed using very few different S–N curves, mainly to capture different environments.

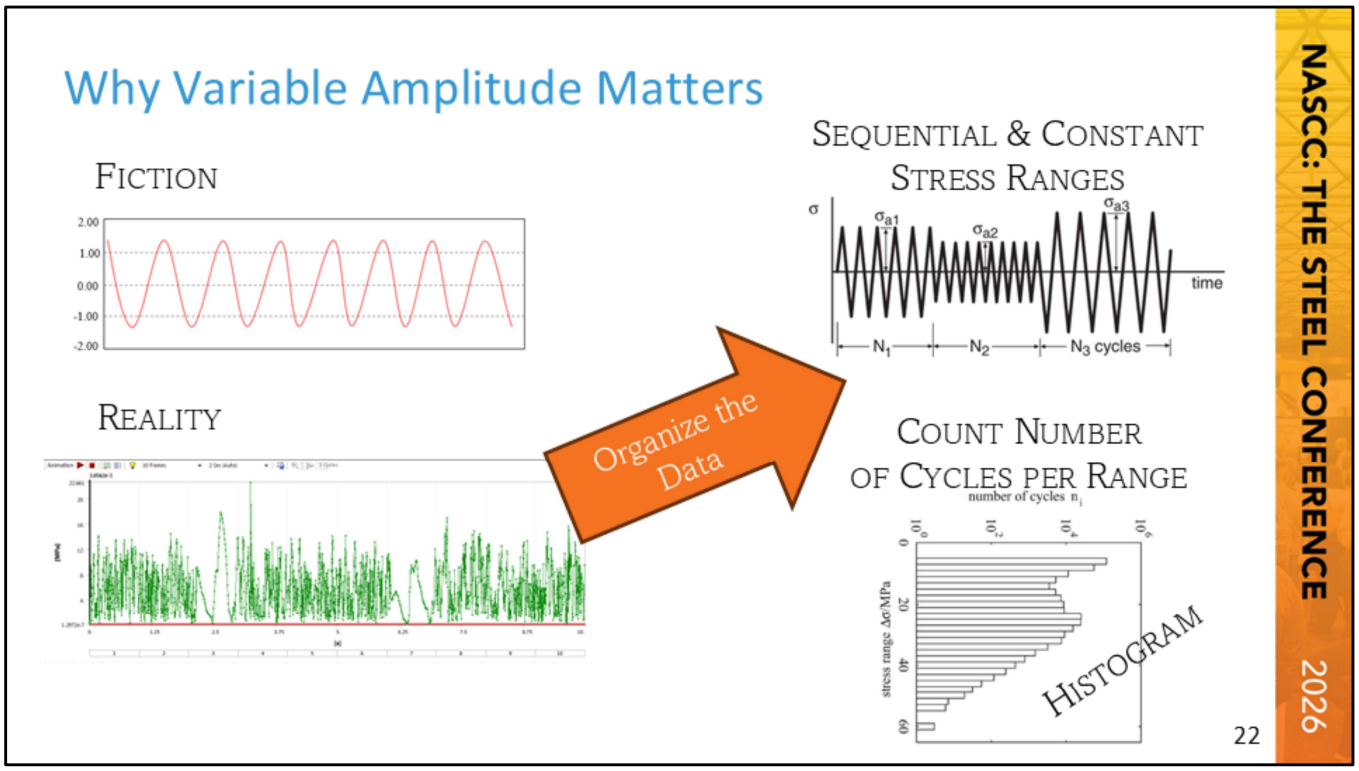
It is important to note that this approach is primarily intended for welded details and does not directly cover fatigue behaviour in the parent material away from welds. Those must be checked by other methods such as via the hot-spot stress. Also, effects such as misalignments are not implicitly included and must be *explicitly* modelled if relevant.

So why is this method used? One of the main reasons is to reduce the conservatism associated with simpler methods. In the nominal and even in the hot-spot stress approaches, many uncertainties related to local geometry and fabrication are embedded in the S–N curves, which can lead to conservative results. The effective notch stress method, by explicitly modelling the local geometry and stress field, provides a more direct assessment of the fatigue behaviour.

This can be particularly useful for critical details, optimized designs, or situations where the standard methods indicate insufficient fatigue life, but a more refined analysis may justify the design.

Overall, the effective notch stress method offers increased precision and reduced conservatism, but at the cost of higher modelling effort and stricter analysis requirements…

Well, I thank you for now and Rafael, my associate, will continue the presentation from the next slide.



Hello Everyone. I know fatigue is a very tiresome subject – but we are halfway there!
So, up to this point, we have been discussing fatigue under the assumption of constant amplitude loading, where the same stress range is repeated throughout the life of the structure.

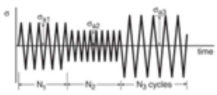
This pleasant fiction is very useful for understanding the methods, but it does not represent how most real structures actually behave. In the real world, loading is crazy irregular and continuously changing over time.

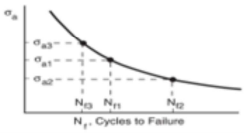
If we look at a real stress time history—like the one shown here—we can see that it is not easy to even define what a "cycle" is. The amplitudes vary, the sequence is not uniform, and the loading is often influenced by multiple sources acting simultaneously.

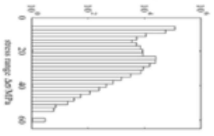
This complexity makes fatigue assessment much more challenging, because we need a way to transform this irregular signal into something that can be used with the methods we spoke about earlier.

Knowing that the real loading is messy, we use tools to process it into a form we can use. Which normally means assuming a sequential constant stress ranges and number of cycles in an organized manner.

Damage Accumulation Concept







Stress Range	N Cycles to failure	Happens n times	Damage
50	10000	1000	10%
10	50000	10000	20%
100	1000	150	15%

MINER'S RULE $$damage = \sum_{m=1}^{k} \frac{n_m}{N_m} = 45\%$$

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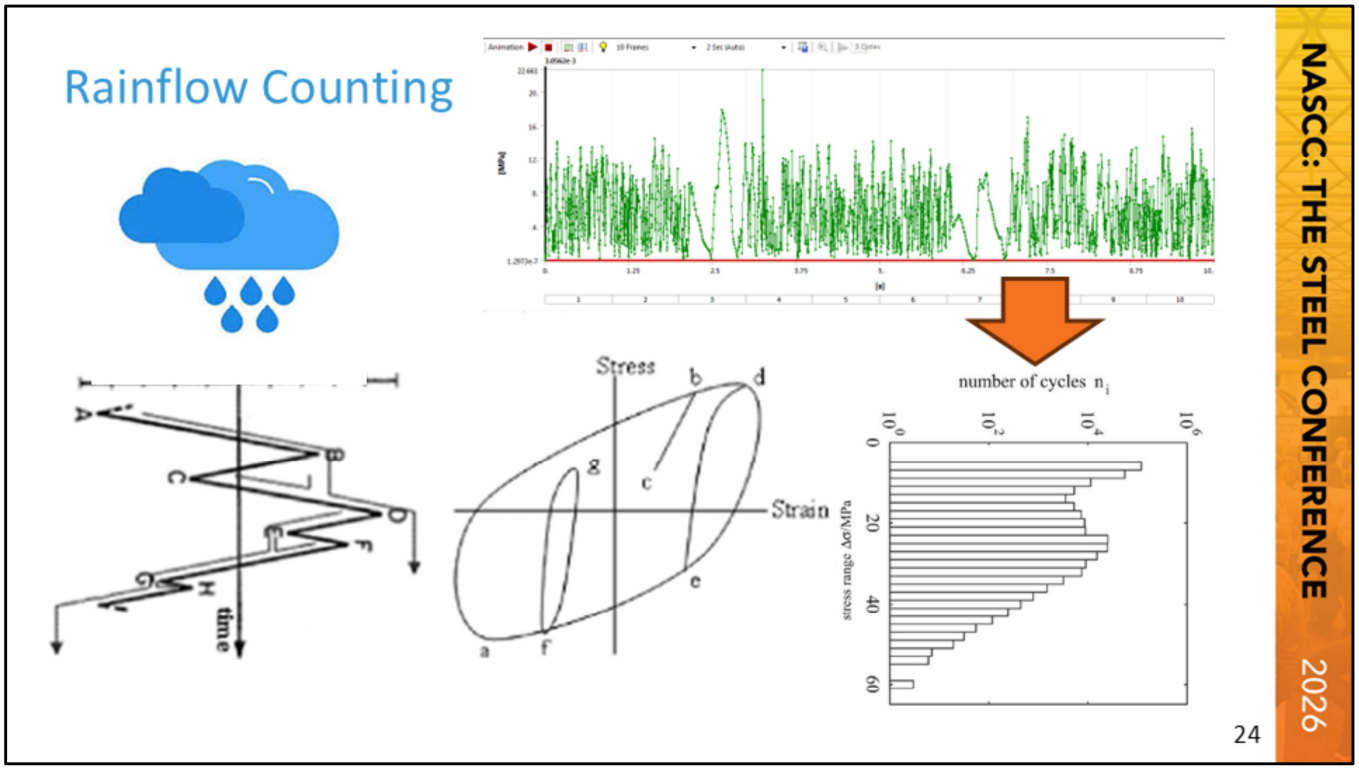
The central concept that allows us to perform a fatigue assessment with variable amplitude loading is the accumulation of the "**linear cumulative damage**." The idea is that each stress cycle causes a small amount of irreversible material degradation, and that this degradation accumulates until failure occurs.

So, we introduce the concept of "*damage*". This damage accumulates in a linear and independent manner, meaning that each cycle contributes the same to the overall damage regardless of the order in which they occur. This is an approximate simplification. Real fatigue behavior can show differences due to sequence and nonlinearities, specially for high stress ranges with low cycles. But the approximation, called Miner's Rule, has been proved to provide reasonable results for high-cycle fatigue, which is what we have in engineering design.

Damage is a normalized quantity, where zero represents an undamaged state and one represents failure. Thus, in this example, 45% of the life was already consumed.

The takeaway here is that: all variable amplitude fatigue methods, no matter how complex, are essentially trying to transform an irregular load history into a stress range histogram with stress range and cycle count. Some methods do it by carefully counting the cycles, while others use statistical approaches.

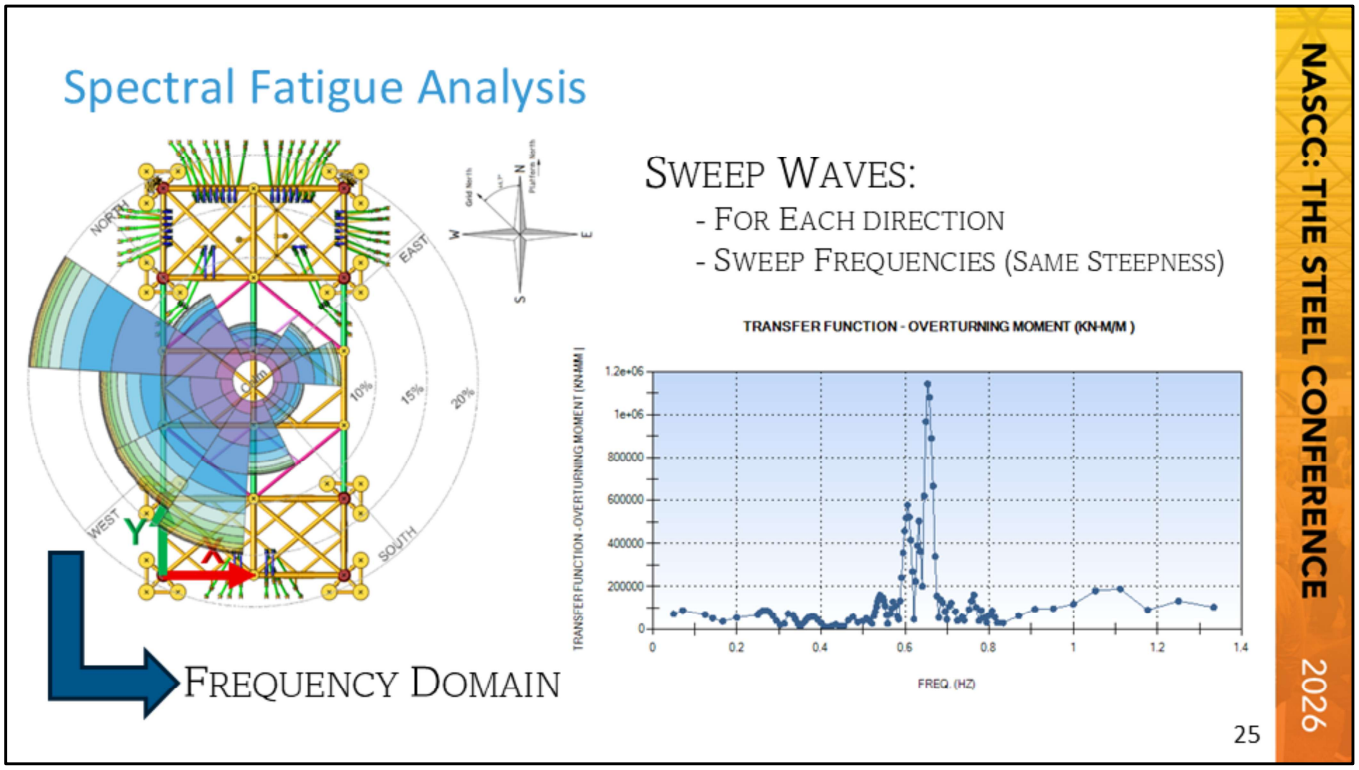
But in the end, they all just want to reach a format where the Miner's rule can be applied.



One of the most widely used methods to process variable amplitude loading is called rainflow counting. Its purpose is to take a complex stress time history and convert it into the stress range histogram.

The name “rainflow” comes from a classical analogy, but in my opinion the analogy is more confusing than helpful.
What really matters for this presentation is the basic idea:
That we can get the histogram with the range of stresses and the counting of cycles from this irregular stress signal.

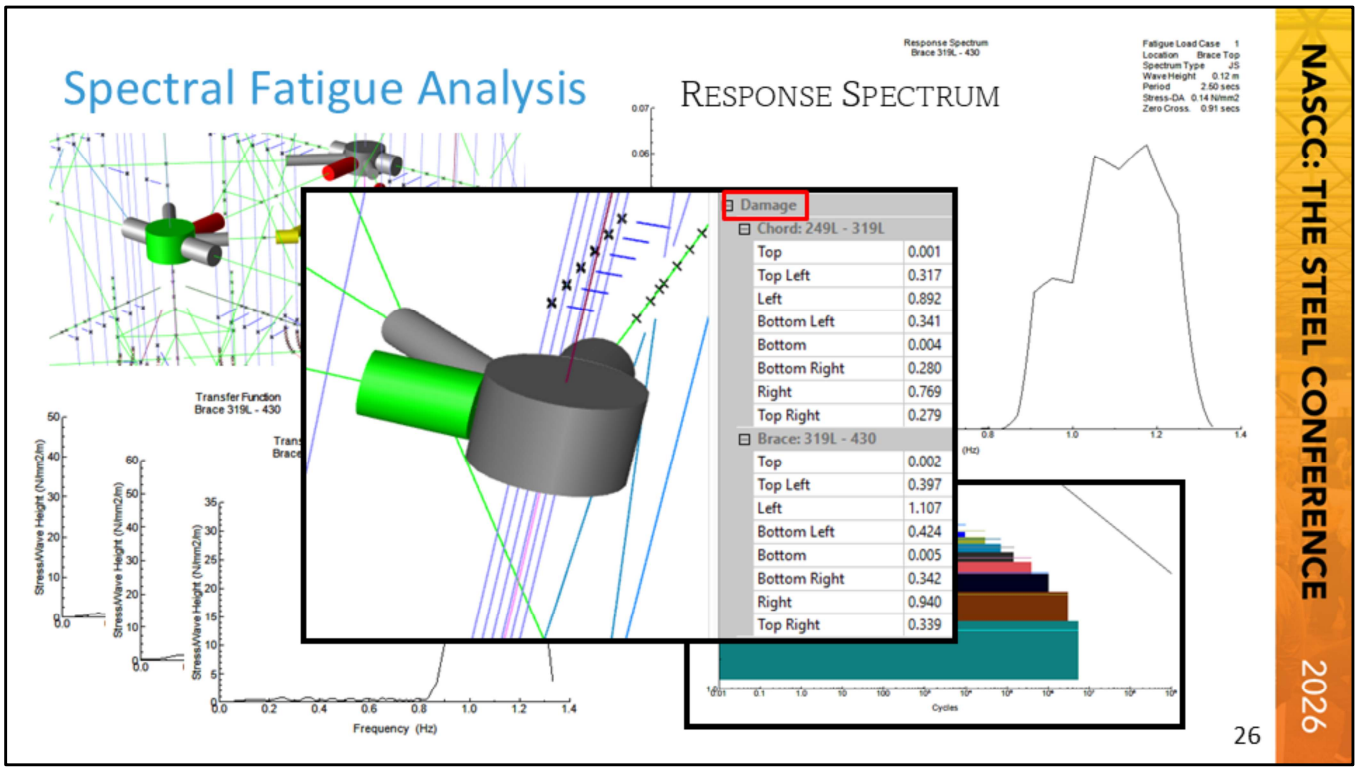
And the famous rainflow counting algorithm does just that.



There are structures that are entirely subjected to variable loading, such as an offshore structures. From having waves hitting from all directions, it becomes almost impossible to define, using engineering judgment which joints, and locations at each joint, that are critical for fatigue design. So normally we do a comprehensive design sweeping through all locations.

A method commonly used for that is called *Spectral Fatigue.* It is a frequency domain analysis that allows us to properly check all joints of a complex structure under random loading such as the waves.

In this method the model is dynamically solved for many wave loadings, sweeping across the frequencies of interest. Outputs are collected across all these wave solutions to generate the transfer functions. The transfer function is a frequency domain function that relates the input (in this case, the seastate in one direction) with an output of the structure. The nice thing is that we can have transfer functions for *any* output. This transfer function that we see here is for overturning moment of the entire structure. BUT



We can also have the transfer functions relative to the hot-spot stresses that we see at the welds of the joints.

For example, in this weld between the leg and the horizontal brace, we have a transfer function for the hot-spot stress at the Top of the brace **<<NEXT CLICK>>**

Another one for the bottom of the brace **<<NEXT CLICK>>**

And, why not, another one at the top of the leg.

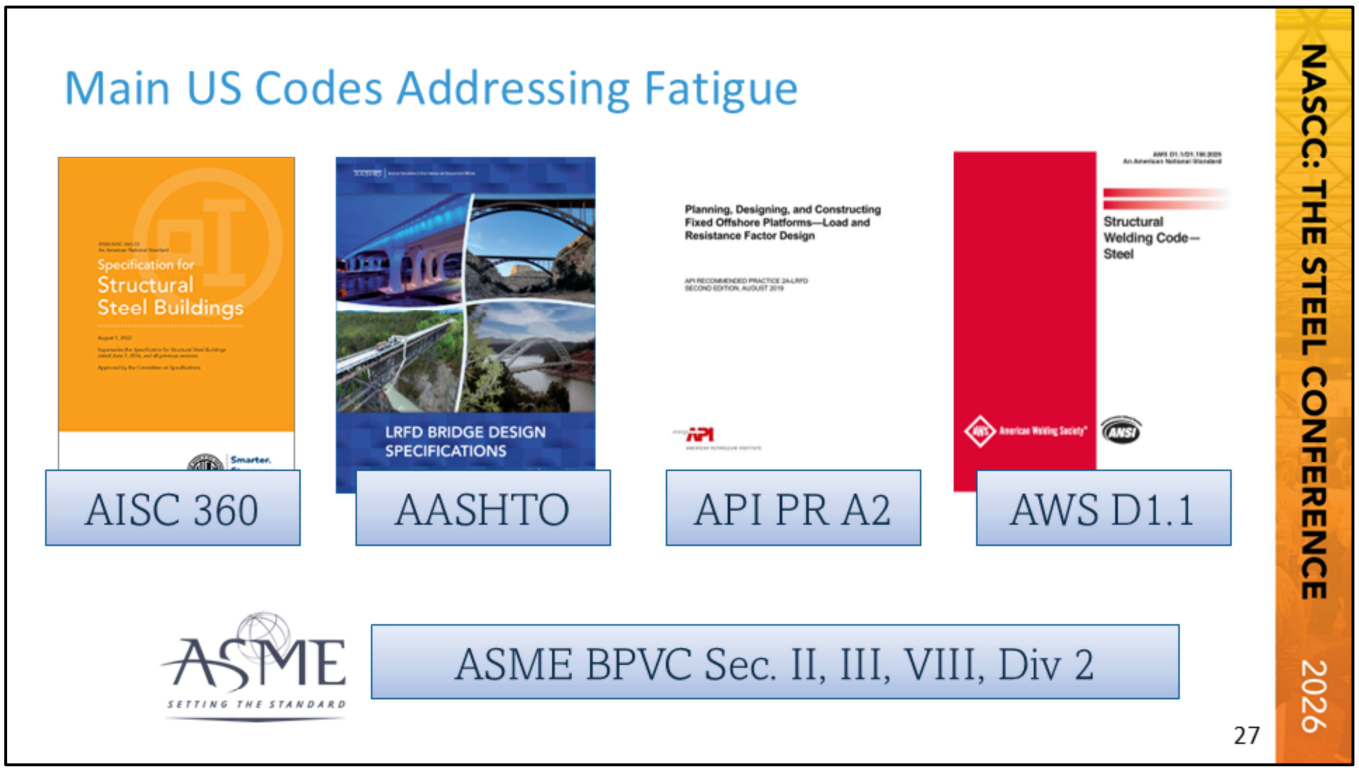
<<NEXT CLICK>>

By multiplying the transfer function with the input wave spectrum, we get the response spectrum at each one of the locations. Although the response is also in the frequency domain; it is possible to apply statistical tools that extract the stress ranges and number of cycles, giving us the histogram as shown.

<<NEXT CLICK>>

Now that we have the histogram, we use the S-N curves to get the damage, at that specific member, at that specific location.

Therefore, we have for all joints all the damage information we want. *Yay!*



In the next slides we will cover some specific provisions from the structural codes related to fatigue.

For the most common cases such as buildings, roofs, etc, the primary reference in this context is of course the AISC 360. For bridge structures, the governing code is the AASHTO LRFD Bridge Design Specifications.

For more specialized applications, such as offshore or industrial, we have other, more detailed, standards such as the API RP 2A for offshore platforms, and the AWS D1.1 Structural Welding Code, which also includes fatigue-related provisions for welded details.

For complex cases, ASME codes are also relevant, particularly for mechanical components and damaged structures.

AISC Fatigue Provisions

TABLE A-3.1 (continued)
Fatigue Design Parameters

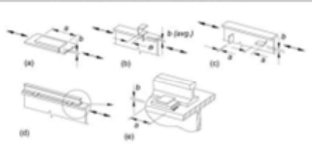
Description	Stress Category	Constant C_f	Threshold F_{TH} ksi (MPa)	Potential Crack Initiation Point
SECTION 7—BASE METAL AT SHORT ATTACHMENTS[a]				
7.1 Base metal subject to longitudinal loading at details with welds parallel or transverse to the direction of stress, with or without transverse load on the detail, where the detail embodies no transition radius, R, and with detail length, a, and thickness of the attachment, b:				Initiating in base metal at the weld termination or at the toe of the weld extending into the base metal
$a < 2$ in. (50 mm) for any thickness, b	C	44	10 (69)	
2 in. (50 mm) ≤ a ≤ lesser of 12b or 4 in. (100 mm)	D	22	7 (48)	
a > lesser of 12b or 4 in. (100 mm) when b ≤ 0.8 in. (20 mm)	E	11	4.5 (31)	
a > 4 in. (100 mm) when b > 0.8 in. (20 mm)	E′	0.39	2.6 (18)	
7.2 Base metal subject to longitudinal stress at details attached by fillet or PJP groove welds, with or without transverse load on detail, when the detail embodies a transition radius, R, with weld termination ground smooth:				Initiating in base metal at the weld termination, extending into the base metal
$R \geq 2$ in. (50 mm)	D	22	7 (48)	
$R < 2$ in. (50 mm)	E	11	4.5 (31)	

TABLE A-3.1 (continued)
Fatigue Design Parameters

Illustrative Typical Examples

SECTION 7—BASE METAL AT SHORT ATTACHMENTS[a]

7.1

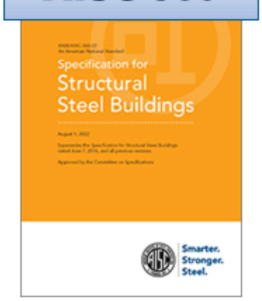


7.2

NOMINAL STRESS METHOD

[…] CALCULATED STRESSES SHALL BE BASED UPON ELASTIC ANALYSIS. STRESSES SHALL NOT BE AMPLIFIED BY STRESS CONCENTRATION FACTORS FOR GEOMETRICAL DISCONTINUITIES. […]

AISC 360



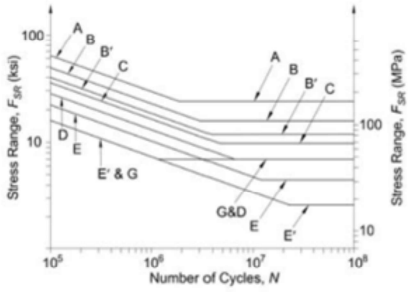


Fig. C-A-3.1. Fatigue resistance curves.

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Let's now look more specifically at how the AISC treats fatigue. We can say that the fatigue provisions in AISC 360 are fundamentally based on what the fatigue theory calls the nominal stress method, so many of the concepts we discussed earlier do apply directly here.

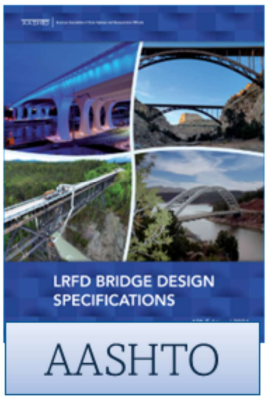
The code requires that stresses be calculated using elastic analysis, and fatigue verification is performed by comparing the nominal stress range against detail categories defined in tabulated S–N curves. These detail categories implicitly account for typical stress concentrations and imperfections.

In addition to the analytical checks, the AISC also includes important considerations related to fabrication and detailing, thus recognizing that fatigue performance is highly influenced by weld quality, detailing practices, and overall execution.

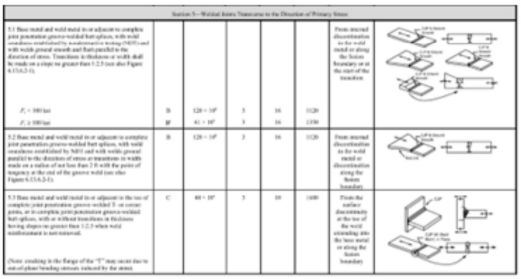
One detail of the AISC specification is that it doesn't give direct and explicit guidance for variable amplitude loading, thus engineering interpretation is necessary.

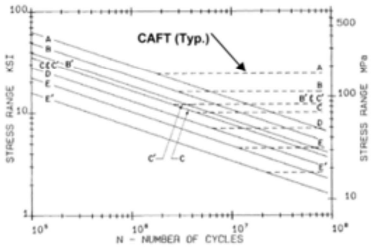
Overall, AISC provides a practical and widely applicable framework for fatigue assessment, but its correct use depends on the understanding of the assumptions behind the nominal stress method.

AASHTO Fatigue Philosophy



NOMINAL STRESS METHOD





CONSIDERS VARIABLE AMPLITUDE LOADING

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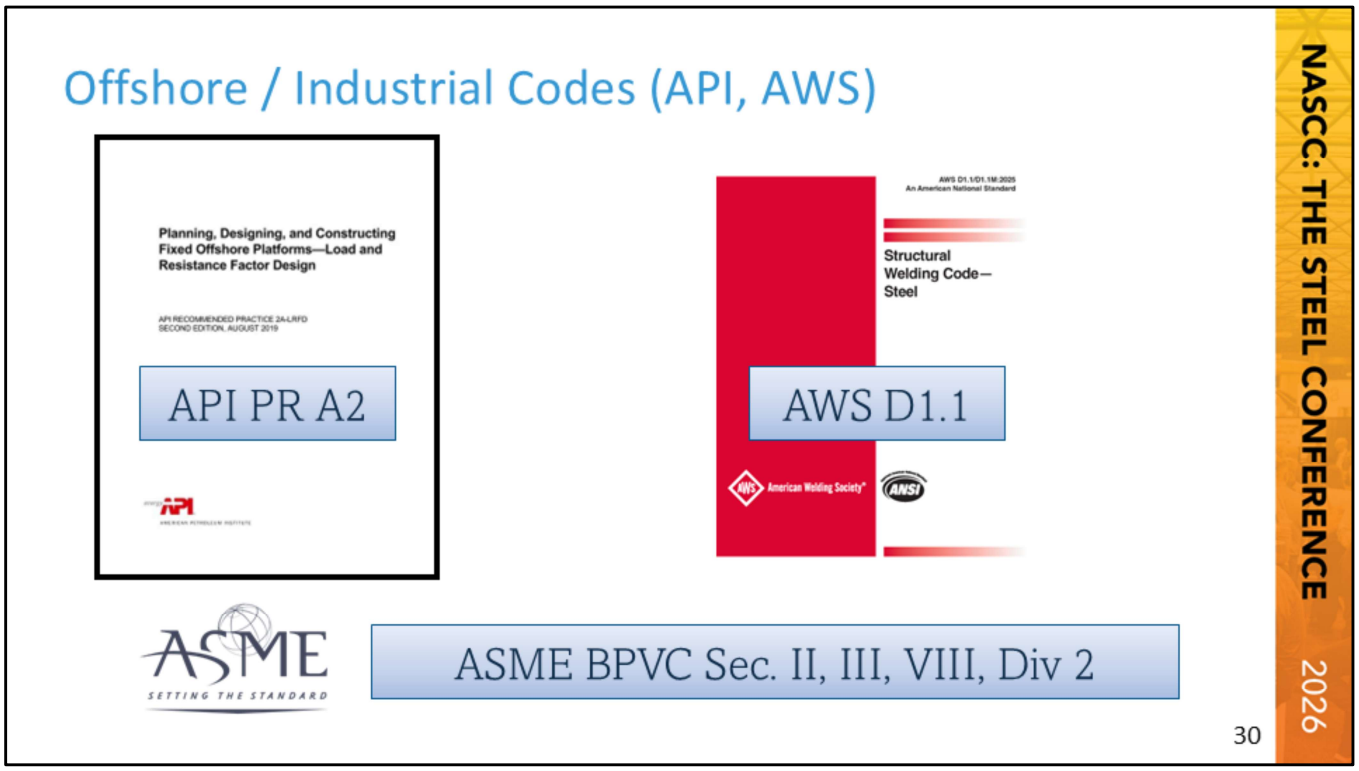
The AASHTO fatigue provisions, primarily developed for bridge design, follow a similar nominal stress-based framework, but are generally more comprehensive than the AISC's when it comes to fatigue assessment.

Makes sense; bridge structures are inherently fatigue-sensitive due to repeated traffic loading.

AASHTO not only provides detail categories and associated S–N curves but also gives explicit guidance on how to deal with real-life variable amplitude loading. In particular, it defines traffic load models that can be used to derive stress range histograms. This allows engineers to move beyond constant amplitude assumptions and evaluate cumulative fatigue damage in a more realistic way.

So, while the underlying method is still based on the nominal stress, AASHTO extends it with practical tools to handle variable loading.



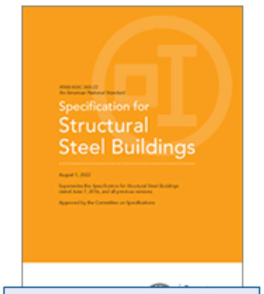
For offshore and industrial applications, codes such as API and AWS provide much more comprehensive fatigue frameworks. These standards go beyond the simplified approaches typically used in building design. They describe, in detail, multiple fatigue assessment methods, and fracture mechanics.

They also provide clear procedures for dealing with variable amplitude loading, including cycle counting methods and cumulative damage using Miner's rule.

While these codes are not part of the day-to-day routine for most engineers working on buildings, roofs, or typical steel frames, they are extremely valuable references when more complex fatigue problems arise.

In situations where standard building codes do not provide sufficient guidance, these offshore and industrial standards can offer the level of detail and methodology needed to properly assess fatigue behavior.

Comparison of EN and AISC360 Codes – Methods



AISC 360

DIRECT APPLICATION OF NOMINAL STRESS METHOD

PRACTICAL AND FOCUSED

Eurocodes

ALL S-N METHODS

COMPREHENSIVE BUT CAN BE OVERWHELMING

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When comparing the Eurocodes, with AISC 360, one of the main differences lies in the scope and level of detail of the fatigue assessment methods that are provided.

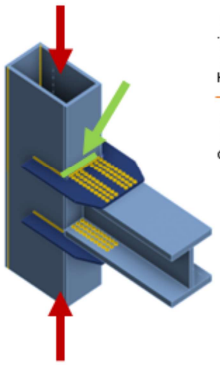
The Eurocodes takes a broader and more comprehensive approach, explicitly covering multiple analysis methods, along with detailed guidance on modeling, stress extraction, and limits of application. This makes it suitable for a wide range of structural problems, including more complex or non-standard details, and allows the engineer to select the level of refinement that best fits the problem at hand.

On the other hand, AISC follows a more focused approach, resulting in a more streamlined and accessible framework for typical structural applications, where detailed and highly refined fatigue analyses are often not necessary nor justified from a practical standpoint.

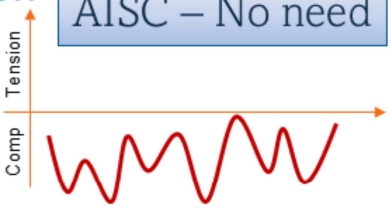
In that sense, AISC provides a more curated set of tools, which avoids overwhelming the engineer with too many different methods. But at the cost of some reduced flexibility when dealing with more complex fatigue

problems.

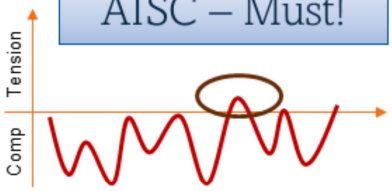
Comparison of EN and AISC360 - Consideration of Compression



AISC – No need



AISC – Must!



AISC 360 2022 – Appendix 3 – Commentary

3.2. CALCULATION OF MAXIMUM STRESSES AND STRESS RANGES

Fluctuation in stress that does not involve tensile stress does not cause crack propagation and is not considered to be a fatigue situation. ***On the other hand, in elements of members subject solely to calculated compressive stress, fatigue cracks may initiate in regions of high tensile residual stress. In such situations, the cracks generally do not propagate beyond the region of the residual tensile stress, because the residual stress is relieved by the crack. For this reason, stress ranges that are completely in compression need not be investigated for fatigue.*** For cases involving cyclic reversal of stress, the calculated stress range must be taken as the sum of the compressive stress and the tensile stress caused by different directions or patterns of the applied live load. When part of the stress cycle is compressive, the stress range may exceed 0.66Fy.

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An interesting difference between Eurocodes and the AISC is in how the effect of compression is treated.

In Eurocode, fatigue is generally considered to be driven by the full stress range, regardless of whether the stress fluctuation occurs entirely in compression or not. This is based on the understanding that, as mentioned before, the residual stresses from welding are typically tensile and they remain locked into the material. As a result, the stress at the critical weld locations remains effectively tensile, thus allowing crack propagation to occur.

For this reason, the beneficial effects of compression is only allowed by the Eurocodes in non-welded details, or in welded components that have undergone thermal treatment after welding.

On the other hand, AISC takes a different approach. While it also acknowledges the presence of tensile residual stresses in the heat affected zone, it assumes that once a crack initiates and begins to propagate, these residual stresses are effectively relieved at the crack tip.

Based on this assumption, AISC allows fatigue checks to be neglected entirely if the stress range does not include any tensile stress—meaning that purely compressive stress cycles are not considered damaging. But it is important to mention that, even if a small part of the stress range lies in tension, the proper

fatigue evaluation must be performed using the full range, since cracks may still propagate.

Comparison of European and America Codes for Wind

Eurocode 1: Actions on structures —

Part 1-4: General actions — Wind actions

Eurocodes

DIRECT CALCULATION OF NUMBER OF CYCLES

B.3 Number of loads for dynamic response

(1) Figure B.3 shows the number of times N_g, that the value ΔS of an effect of the wind is reached or exceeded during a period of 50 years. ΔS is expressed as a percentage of the value S_k, where S_k is the effect due to a 50 years return period wind action.

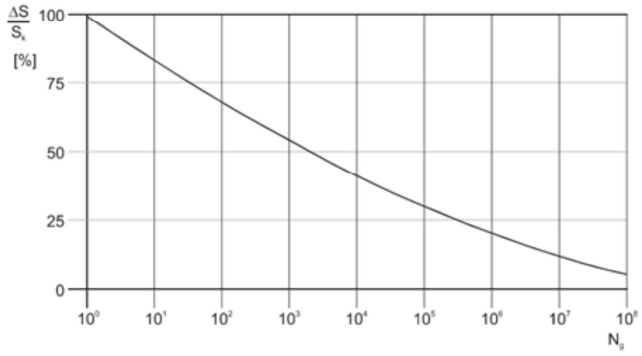

Figure B.3 — Number of gust loads N_g for an effect $\Delta S/S_k$ during a 50 years period

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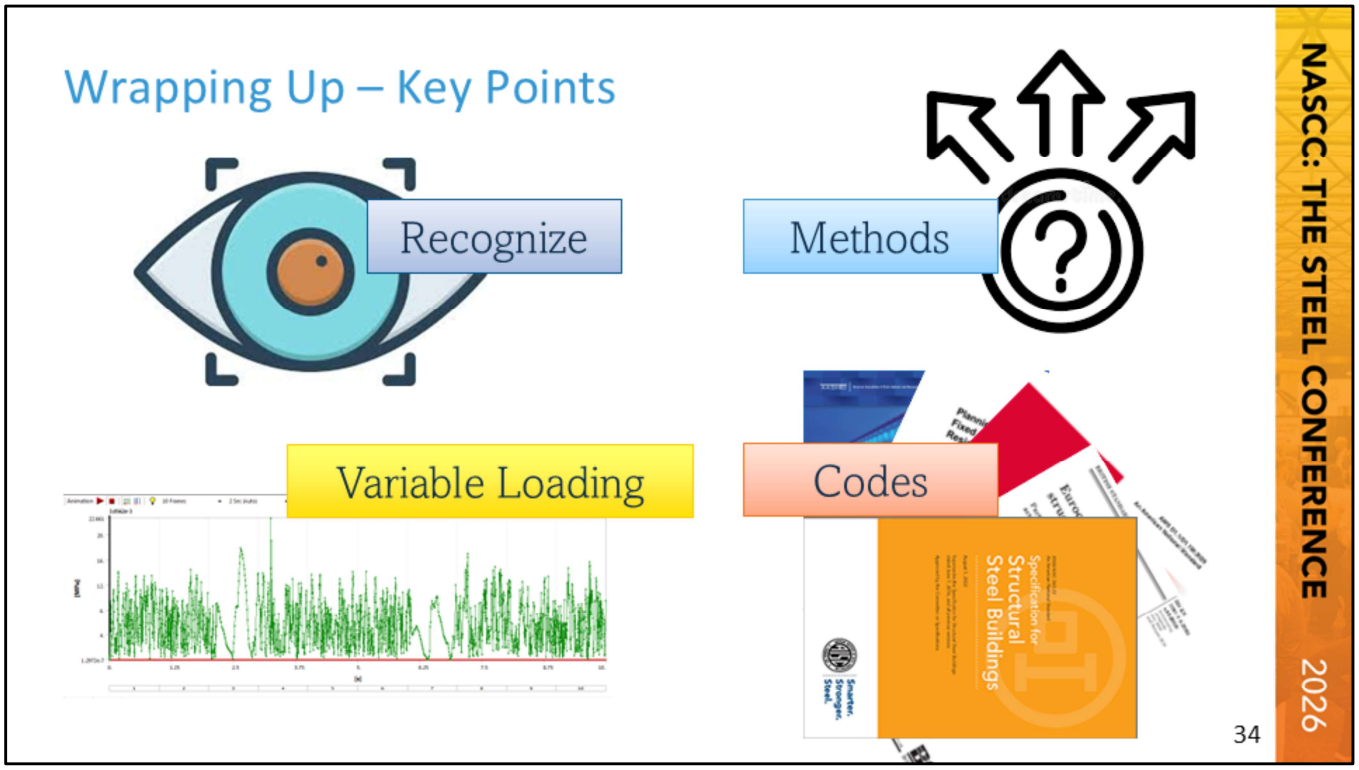
When it comes to wind-induced fatigue, both the Eurocodes and the American standards provide the necessary information to perform a proper fatigue assessment, but they do it in different ways.

The Eurocode for Wind Loading directly provides cumulative distributions of the number of times that a given stress range is exceeded over 50 years. This type of information can be readily converted into a stress range histogram to be used in fatigue damage calculations. This makes it relatively straightforward to screen structures for wind-induced fatigue.

On the other hand, ASCE 7 provides a more theory-based framework. It includes the necessary background to derive the structural response from wind, such as wind power spectral density functions and coherence functions, which are used to calculate of the structural response in the frequency domain. However, translating the wind power spectral density into the stress range histogram requires additional steps and significant numerical effort.

So, while both codes contain the necessary ingredients, Eurocode offers a

more direct pathway for fatigue assessment of wind loading, whereas ASCE 7 requires a more detailed analytical process.



Well, Yeah… I can the damage caused by the stress from all these slides has been accumulating. You guys are probably reaching your fatigue life. So, let's wrap up.

The key points we hope you will take away from this presentation are:

First, **Recognize**: Fatigue is not something we deal with in every project. But it can govern the design when it is relevant. So, recognizing when it matters is essential.

Second, **Methods**: There isn't a single fatigue method—multiple approaches exist. From the simple nominal stress method to more advanced techniques such as crack propagation. Selecting the right one depends on the problem and the level of detail required.

Third, **Variable Loading**: Real structural loading is not constant. So, understanding how to process variable amplitude loading into a stress range histogram is a central part of fatigue assessment.

And finally, **Codes**: From the code perspective, different standards consider fatigue in different ways; with different levels of detail.

Credits for the visuals

Slide	Source	Link
4	Sarens	https://www.sarens.com/about/news/sarens-handles-jackets-for-nearly-na-gaoithe-offshore-wind-farm.htm
4	Tennet	https://www.mcdermott.com/projects/tennet-balwin4-lanwin1
4	ISSUU	https://issuu.com/ivgroep/docs/brochure_offshore_wind_solution/s/21456074#:~:text=The%20o%20shore%20substation%20is,Accommodation
4	power-technology	https://www.power-technology.com/projects/borssele-windfarms-1-2/
5	Sparrows	https://www.allradsparrows.com/news-and-updates/structural-fatigue-in-cranes
5	Mankato Man	https://www.facebook.com/MrMankato/posts/the-i-35-bridge-collapse-is-old-enough-to-vote18-years-ago-today-the-bridge-fail/800773082599573/
9	CambridgePolymer	https://www.youtube.com/watch?v=GPYw8hRkyVA
8	Metallurgical engineering	https://www.instagram.com/reel/DOXoM4YjP-b/
9	Metallurgical engineering	https://www.facebook.com/watch/?v=866104513056934
9	Profiles of persistent slip markings and internal structure of underlying persistent slip bands. J Polák, V Mazánová, M Heczko, I Kuběna, J Man	
12	F.Learning Studio	https://www.youtube.com/watch?v=k3VV0No3Jlg
12	Heat Treat Today	https://www.heattreattoday.com/ask-the-heat-treat-doctor-post-weld-heat-treating-why-is-it-necessary-and-how-do-we-perform-it/
12	Application of fracture mechanics to welds with crack origin at the weld toe: a review Part 1: Consequences of inhomogeneous microstructure for materials testing and failure assessment, U Zerbst	https://link.springer.com/article/10.1007/s40194-019-00801-5
13	HST Group	https://www.hsdgroup.com/VIDEO/fatigue_testing_machine_video/
13	Metallurgical engineering	https://www.instagram.com/reel/DOXoM4YjP-b/
14	By Sclafertiere - Own work, CC BY-SA 4.0	https://commons.wikimedia.org/w/index.php?curid=148773948
14	Tennet	
16	F.Learning Studio	https://www.youtube.com/watch?v=k3VV0No3Jlg
16	L.B. Malefane: HIGH CYCLE FATIGUE PROPERTIES OF AS-BUILT TI6AL4V (ELI) PRODUCED BY DIRECT METAL LASER SINTERING	
18	FEA Stress Determination for Weld Fatigue Using Hot-Spot Stress Method: Benchmarking and Rail Application | IIETA:	https://www.iieta.org/journals/ijcmem/paper/10.18280/ijcmem.120301
23	Oswald, Markus; Mayr, Christina; Rother, Klemens	Determination of notch factors for welded cruciform joints -- Oswald, Markus; Mayr, Christina; Rother, Klemens -- Welding in the World, #5, 63, pages -- 10_1007_s40194-019-00751-y -- 2a01288eb6321
23	Main Takeaways on Stress and Strain Concentrations - TU Delft OCW:	https://ocw.tudelft.nl/course-readings/6-3-5-main-takeaways-on-stress-and-strain-concentrations/
25	Determination of notch factors for welded cruciform joints -- Oswald, Markus; Mayr, Christina; Rother, Klemens -- Welding in the World, #5, 63, pages -- 10_1007_s40194-019-00751-y -- 2a01288eb6321	
26	Fatigue Analysis using History Data	https://innovationspace.ansys.com/forum/forums/topic/fatigue-analysis-using-history-data/
27	22 Use of the Palmgren-Miner rule for life prediction for variable... | Download Scientific Diagram	https://www.researchgate.net/figure/Use-of-the-Palmgren-Miner-rule-for-life-prediction-for-variable-amplitude-loading-which_fig17_339935670

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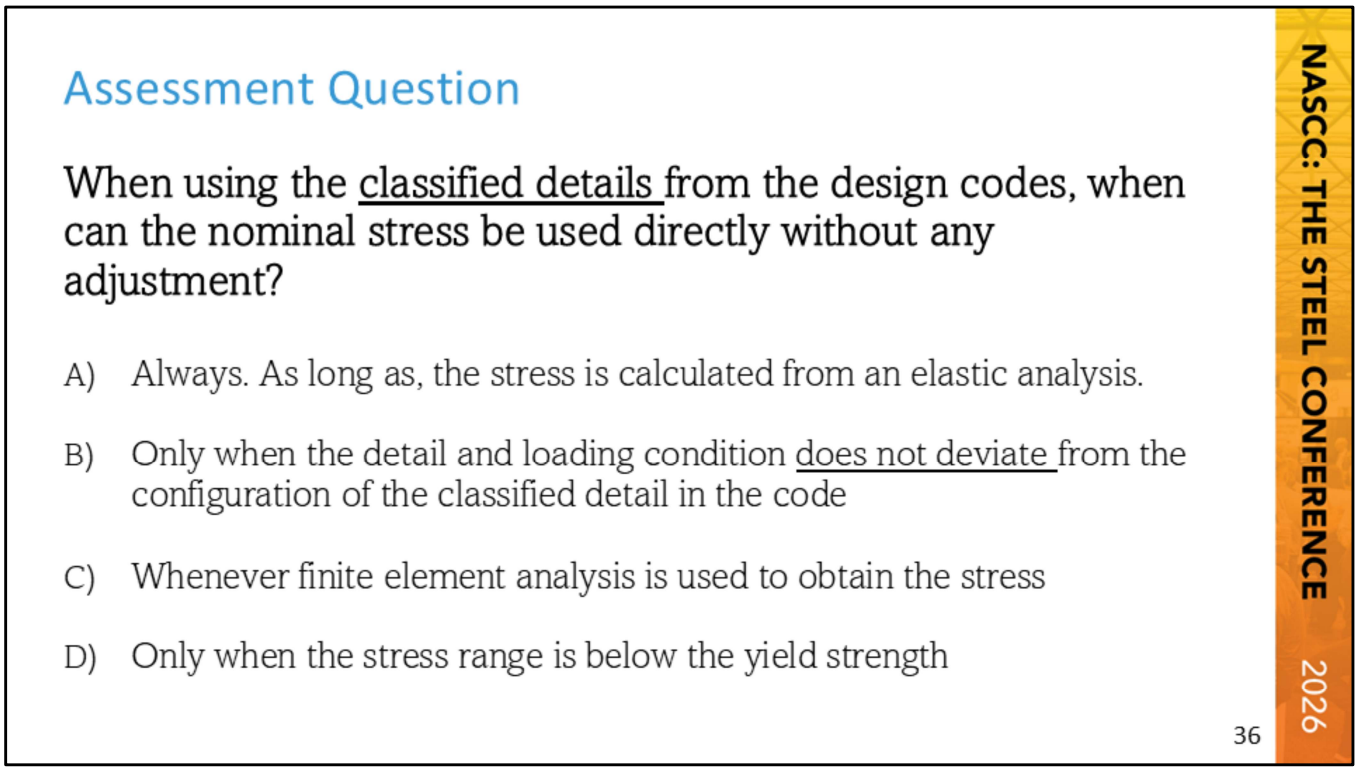
Some of the visuals of this presentation have been taken from the web; so here we acknowledge their sources.



We wrap this up with our quick assessment question. The Question is:

When using the classified details from the design codes, when can the nominal stress be used directly without any adjustment?

A) Always, as long as the stress is calculated from an elastic analysis
B) Only when the detail and loading condition does not deviate from the configuration of the classified detail in the code ✅
C) Whenever finite element analysis is used to obtain the stress
D) Only when the stress range is below the yield strength

Hands up for A, hands up for B, hands up for C, and hands up for D.

The correct answer is B. This is a critical nuance, because using the nominal stress directly in cases where the actual detail does not match the classification can lead to unconservative results.

With that, we finish the presentation. The PDH code for this presentation is 26128.

Thank you for your attention—and We are happy to take any questions.