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Michał BÖHM*, **Mateusz KOWALSKI***
Faculty of Mechanical Engineering, Opole University of Technology, Poland
* Corresponding authors: m.bohm@po.opole.pl (M. Böhm); m.kowalski@po.opole.pl (M. Kowalski)

CHALLENGES AND NEW AREAS OF DEVELOPMENT FOR THE SPECTRAL METHOD OF FATIGUE LIFE ASSESSMENT

Key words: spectral method, fatigue life assessment, frequency domain.

Abstract: Many computer aided design methods that are being presented in the literature are using advanced fatigue life assessment methods. The problem with the assessment is especially interesting in the moment when the calculations are performed for random loads. In such cases it is common to use one of two calculation methods. The first one is based in the time domain and it uses cycle counting algorithms to assess the damage degree. The second is based in the frequency domain and it uses statistical information to assess the damage degree. Due to the emerging need of industry many fatigue life calculation methods have been developed for both domains. One of these methods is the spectral method for fatigue life assessment. The idea of this method is set in performing calculations in the frequency domain. That means that the operating information are the power spectral density and probability density function of loading amplitudes. Frequency domain fatigue life assessment methods have a young history compared to the time domain methods. Due to this fact many issues which have been solved within the time domain are still an unsolved issue in spectral method. That means that a certain question: why to use spectral method when it has many unsolved issues suddenly emerges. One of the simplest answers to that question is that spectral method is faster, which means that it is more time and money efficient. That was one of the main reasons to perform an analysis of issues that have to be solved, and awaiting challenges of the spectral method. Another question that had to be asked, in regards to the analysis: are there any areas where this method might be the only potentially applicable? The paper is divided into four parts that are taking these questions to further discussion. Some of the presented discussion points might be analyzed in both uniaxial and multiaxial loading condition.

Wyzwania i nowe obszary rozwoju metody spektralnej wyznaczania trwałości zmęczeniowej

Słowa kluczowe: metoda spektralna, wyznaczanie trwałości zmęczeniowej, dziedzina częstotliwości.

Streszczenie: Wiele metod projektowania wspomaganych komputerowo, które są prezentowane w literaturze, wykorzystuje zaawansowane metody oceny zmęczenia konstrukcji. Problem z oceną jest szczególnie interesujący w momencie, gdy obliczenia wykonywane są dla losowych obciążeń. W takich przypadkach często stosuje się jedną z dwóch metod obliczeniowych. Pierwsza opiera się na dziedzinie czasu i wykorzystuje algorytmy zliczania cykli do oceny stopnia uszkodzenia. Druga opiera się na dziedzinie częstotliwości i wykorzystuje informacje statystyczne do oceny stopnia uszkodzenia. Ze względu na pojawiające się potrzeby przemysłu opracowano wiele metod obliczania trwałości zmęczeniowej dla obu dziedzin. Jedną z tych metod jest metoda spektralna oceny trwałości zmęczeniowej. Metoda ta wykorzystuje obliczenia w dziedzinie częstotliwości. Oznacza to, że informacja operacyjna to gęstość widmowa mocy i funkcja gęstości prawdopodobieństwa amplitud obciążenia. Metody oceny trwałości zmęczeniowej w dziedzinie częstotliwości mają młodą historię w porównaniu z metodami w dziedzinie czasu. Z tego powodu wiele problemów, które rozwiązano w dziedzinie czasu, wciąż pozostaje nierozwiązanym problemem w metodzie spektralnej. Oznacza to, że pojawia się pewne pytanie: po co stosuje się metodę spektralną, skoro nadal istnieje tak wiele nierozwiązanych problemów. Jedno z najprostszych odpowiedzi na to pytanie brzmi następująco: metoda spektralna jest szybsza, co oznacza, że jest ona wydajniejsza pod względem czasu i pieniędzy. Był to jeden z głównych powodów do przeprowadzenia analizy zagadnień, które należy rozwiązać, jak również wyzwań stojących przed metodą spektralną. Kolejne pytanie, które należało zadać w odniesieniu do analizy: czy istnieją obszary, w których ta metoda może być jedyną potencjalnie możliwą do zastosowania? Artykuł jest podzielony na cztery części, które stawiają te pytania do dalszej dyskusji.

Introduction

We are at the dawn of a new century, a century where the computer calculations are one of main factors when it comes to construction assessment. Reliability as well as time are of equal value for a computation procedure. We find it interesting how computer aided design methodsare being presented in the literature for advanced fatigue life assessment methods. The problem with the assessment has a deeper meaning when it comes to calculations that are performed for random loads. In such cases we can freely chose between two calculation methods. The first one is based in the time domain and it uses cycle counting algorithms to assess the damage degree [1, 2]. The second method is based in the frequency domain and it uses statistical information to assess the damage degree [3, 4]. Due to the emerging need of industry many fatigue life calculation methods have been developed for both domains. One of these methods is the spectral method for fatigue life assessment. The idea of this method is set in performing calculations in the frequency domain. That means that the operating information is the power spectral density (PSD) and probability density function (PDF) of loading amplitudes [5, 6]. These information are being used in the forming of spectral moments, which are later used for simulation purposes. Frequency domain fatigue life assessment methods are still being developed due to their young age. Due to this fact many arising problems which have been solved for the cycle counting method are still an unsolved issue in spectral method. That means that we can formulate a certain question: why to use spectral method when it has so many unsolved issues? One of the simplest answers to that question is that spectral method is faster, which means that it is more time and money efficient. That was one of the main reasons to perform an analysis of problems that have to be solved, and awaiting challenges of the spectral method. Another question that had to be asked, in regards to the analysis: are there any areas where spectral method might be the only applicable? The discussed problems are present for both cases of uniaxial and multiaxial loading conditions. The paper is divided into four parts that are taking these questions to further discussion. Some of the presented discussion points might be analyzed in both uniaxial and multiaxial loading condition.

1. Signal characteristic

The first issue that arises when we are dealing with the spectral method is the problem with the analyzed signals stationarity. Stationarity defines if certain statistical variables are constant for every moment of the time in regards to the whole signal. For most cases if the autocorrelation function and mean value of the signal is stable, then we can assume that the signal is stationary [7]. For any other scenario the signal is regarded as non-stationary. But when we analyze the literature we can observe that non-stationarity is a non-property [8, 9]. If the signal is purely stationary, then we don't have any problems with the calculations, but when the signal is non-stationary then we have issues when it comes to calculationscause we lose critical information. The problem emerges with the proper calculation of the joint probability distribution, and most of all variance and the mean value. For non-stationary processes we obtain different values of these variables over time. Currently while dealing with those kind of signals we are analyzing them as stationary and because of this fact we are losing information about the loading history. A similar situation occurs when we are analyzing non-gaussian loading signals. The spectral method is generally designed for Gaussian signals, which means that if we are analyzing a non-gaussian signal as a Gaussian, then we are losing information once again. Currently there are certain solutions which are dealing with this problem in terms of adding extra information with the use of a correction factor to the damage degree calculation process presented by Bracessi et al [10]. Another solution is proposing the correction of the non-gaussian signal and with a correction factor by Wolfsteiner and Breuer [11]. Some of these methods have been used in the paper by Niesłony et al [12] to solve the problem of non-gaussianity for stress signals. Nevertheless we have to analyze potential methods that could be used to identify non-stationarity in the spectral method. Some methods arise as a potential tool in identifying stationarity in frequency domain, those methods are generally based on the use of the short time fourier (STFT) analysis or Wold-Cramer decomposition techniques [13]. So the use of the Gabon or Wavelet techniques seems handy due to the fact that they take into account the time information for the transformation. Fig. 1 presents a non-stationary signal, it is impossible to identify the non-stationarity of the signal just by looking on it. That's why we have to run full analysis, but thanks to spectral kurtosis (Fig. 2 presents the signals frequency response PSD and his spectral kurtosis) that has been generated with the use of the function presented by Antoni [8, 9] we can graphically identify if the signal is non-stationary due to the fact that a pure Gaussian stationary signal has a mean spectral kurtosis value around 0. This function is using both Wold-Cramer decomposition and STFT to give us a decent information about the stationarity of the signal. It might be the easiest and cleanest way to identify stationarity in spectral method. We can see that the PSD doesn't take into account the non-stationarity part of the signal and completely eradicates this information. By using the spectral kurtosis we can add information about the non-stationarity to supplement the PSD information.

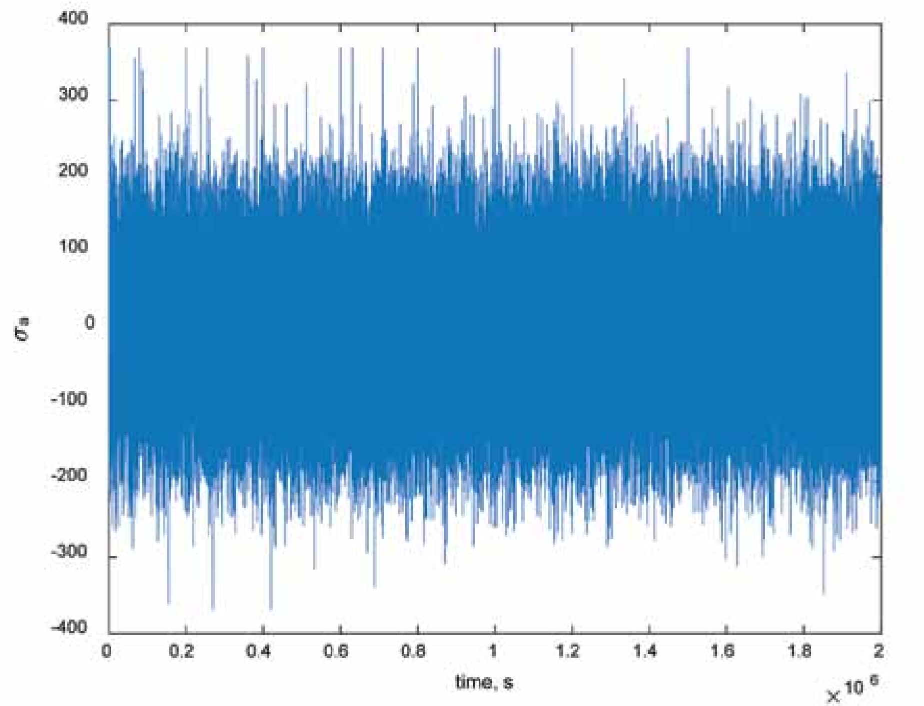

Fig. 1. A non-stationary stress loading history

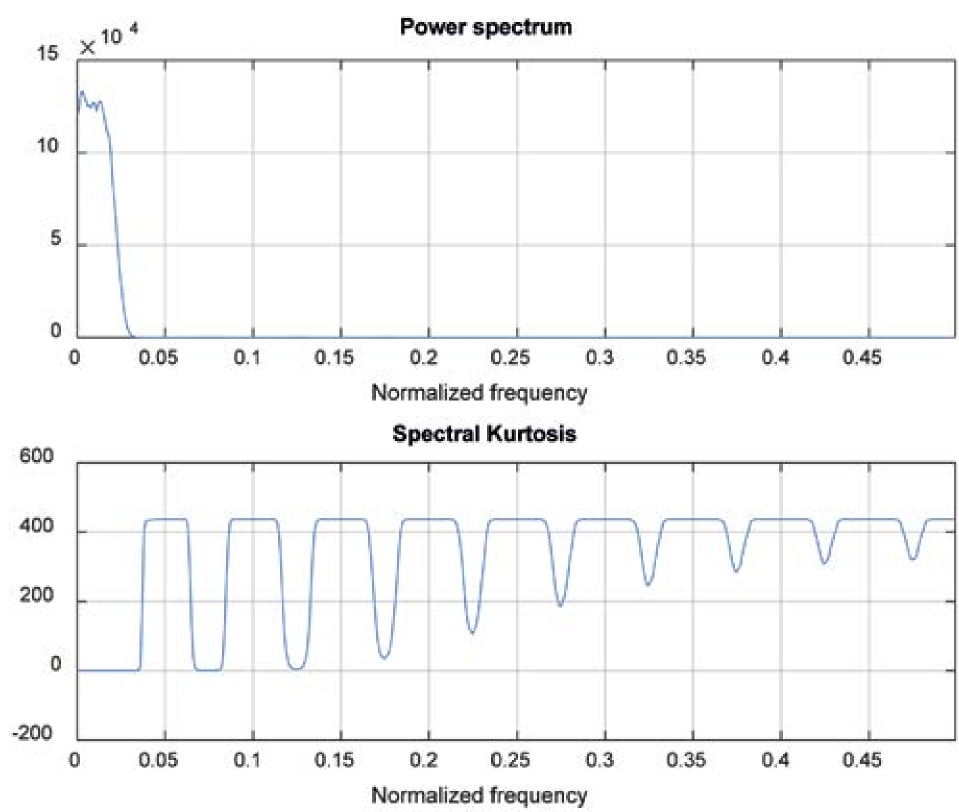

Fig. 2. A non-stationary signals PSD and spectral kurtosis

2. Mean stress correction

The mean stress is inputted to the system as an effect of self load or literately an extra load that is working on the construction. The spectral method for fatigue life assessment is generally not suited for signals with non-zero mean stress history, if we analyze such histories then we obtain a large peak in the power spectral density (PSD) in the zero value region. That peak is not effectively represented in the damage accumulation. Because of this fact we always have to analyze a signal as an zero mean signal. In such cases we are losing information. There are some solutions to this problem that are being presented inter alia by Niesłony and Böhm [1, 2] and Łagoda et al. [14]. The proposed solutions have been proposed for the uniaxial stress state. There is still no solution for taking into account the mean stress in regards to multiaxial fatigue. So the question arises on how to take the influence of mean stress in multiaxial fatigue. Maybe by modifying some multiaxial fatigue criteria that are being used to calculate the equivalent values of stress. Another solution is by maybe modifying the cross spectral density that is being used in the process of multiaxial fatigue assessment by a correction factor. Fig. 3 presents an algorithm of fatigue life assessment proposed by Niesłony and Böhm [1].

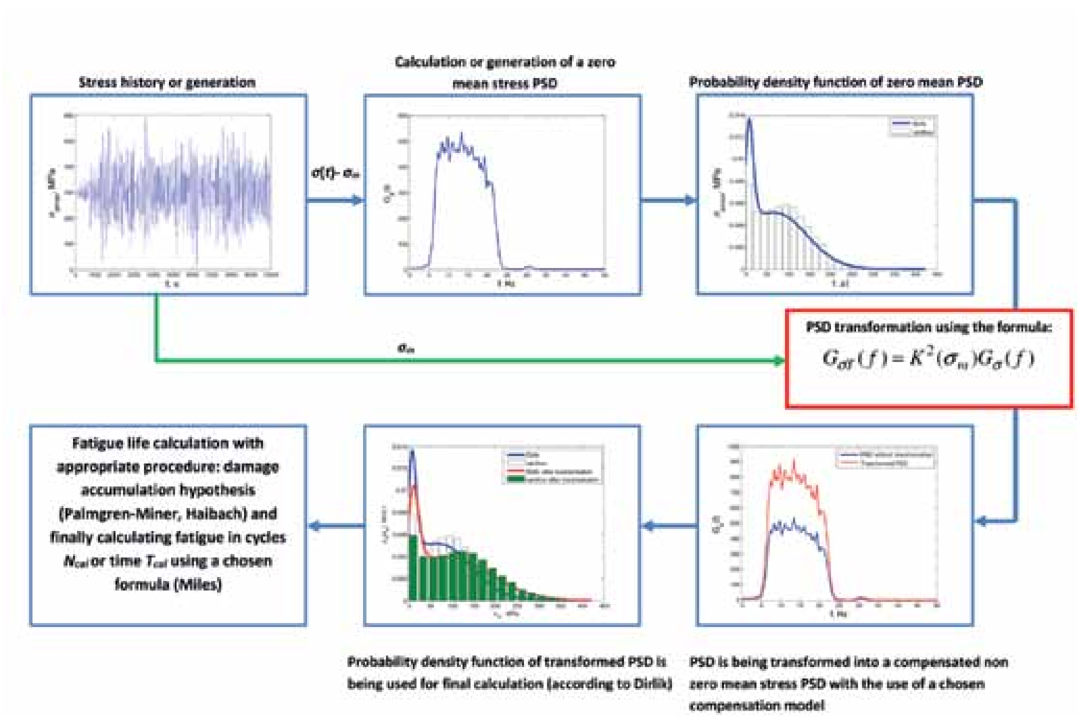

Fig. 3. Fatigue life assessment algorithm for the mean stress compensation in the frequency domain, caluclations for the uniaxial case-taken from the paper by Niesłony and Böhm [14]

3. Material overloading

Material periodic or random overloading is one of the common problems related to loads with a stochastic characteristic. Nevertheless it is still an open issue in regards to fatigue life assessment using the spectral method. Overloading amplitudes are interfering with the plastic zone of the material. Spectral method is rigorously used only for the elastic stress state of material. That means that if we have overloading amplitudes within our loading history even beneath the ultimate stress level, then we cannot properly assess the impact of the overload in regards to the caused damage because those overloading amplitudes are interfering with the plasticity, that means that the material should be analyzed in the elastic-plastic state. Currently there is no simple answer or solution to this topic, but maybe we could perform a correction to the power spectral density (PSD) or probability density function (PDF) of the signal to take into account the missing information about the damage. To perform calculations with the spectral method and to remain within the range of most of the damage hypothesizes, the overloading amplitudes can't be over the value of ultimate strength of material, and not below the border value of stress amplitude that is being used in the relation of the Wöhlercurve [15]. Fig. 4 presents a random stress history with overloading amplitudes. The problem of overloading is complex and is also a non-stationarity problem. The obtained PSD will be degenerated in terms of the missing information about the overloading. Fig. 5 presents the PSD and spectral kurtosis of the overloading signal.

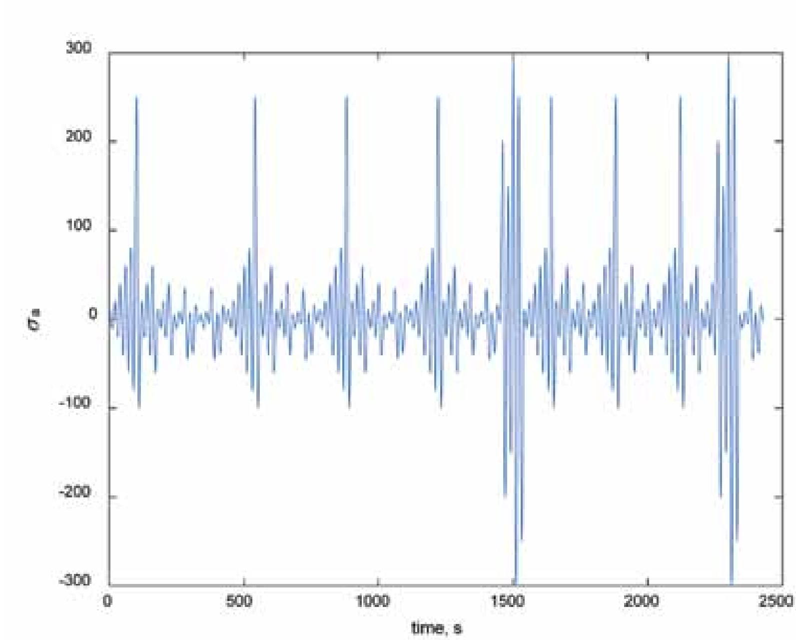

Fig. 4. Stress history with overloading amplitudes

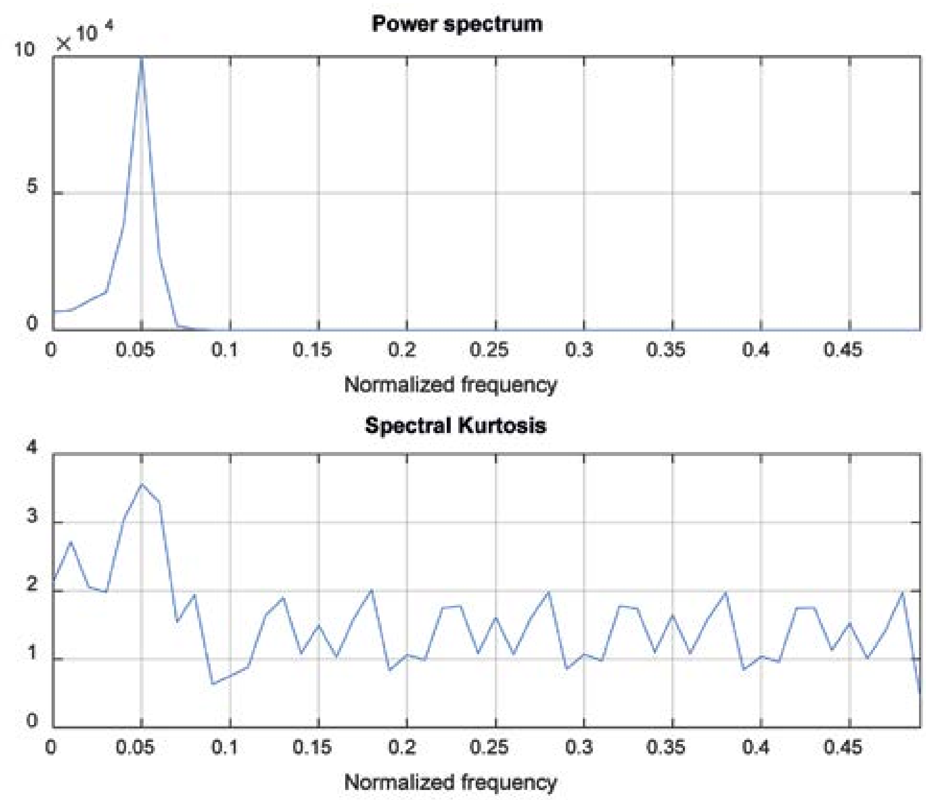

Fig. 5. PSD and spectral kurtosis of the overloading stress history presented in Fig. 4

4. Vibration fatigue and other areas

The literature review clearly shows that spectral method for fatigue life assessment is especially applicable for vibration fatigue analysis. The vibration fatigue tests are usually performed on electromagnetic shakers. The shakers allow high frequency testing therefore we can obtain the area of giga-cycle fatigue for many materials and constructions in a blink of an eye. Besides that, vibration tests allow many materials to be tested in their natural frequencies. The information that we obtain during vibration fatigue tests are especially suited for a frequency domain analysis [16]. We can analyze different PSD's of the signal with this method. Sometimes test are being run with a defined PSD, that means that it is unlikely possible that we will use time domain defined methods for any fatigue related calculations. When it comes to applications, the spectral method is a suitable tool for finite element analysis when we want to create fatigue life maps of constructions. In these terms we only need the PSD of the load and the calculations are being performed in high speed. Another area where the calculations with the spectral method for fatigue life assessment might be handy are in regards to the use of material energy characteristics where we could use the PSD's and PDF's directly to calculate the energy parameter. The energy parameter is a correlation between the stress and strain history of the load [17]. Currently it is possible to use this kind of characteristic with spectral method, but not without the stress and strain loading histories. If we could use just the PDF's or PSD's of the source signals then we could use the energy parameter directly with the spectral method for fatigue life assessment. Another area where this method seems to have more potential is within the fatigue calculations of large structures influenced with wind or sea forces such as the wind energy plants or oil platforms. It is a convenient method of calculations while mostly we have the information about the PSD or PDF of the sea or wind for longer periods, and if we would like to register long enough loading time histories wits strain gauges, then the calculations would be impossible to perform. The spectral method seems to be in that sense a good option for fatigue life assessment of materials that are influenced by specific random PSD's such as the explosive cladded materials that are being used as the ship welding connectors [18]. Fig. 6 presents an example of an explosive welded connector that is being influenced by random loading.

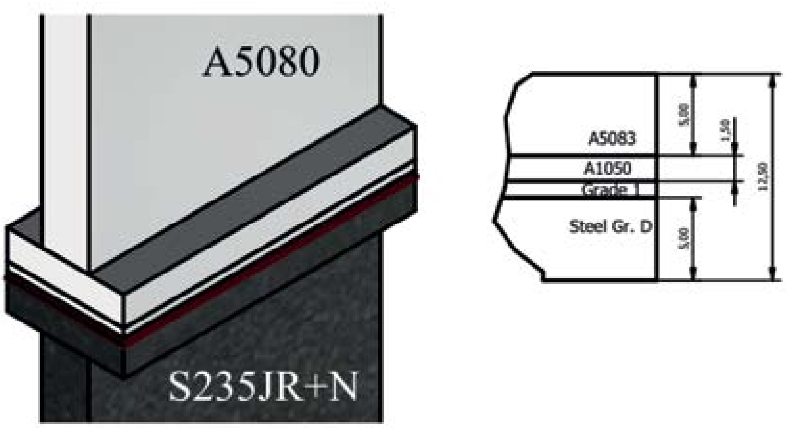

Fig. 6. Explosive welded welding connector A5080-S235JR+N

Conclusions and observations

The discussion about the challenges and areas of potential development of spectral method for fatigue life assessment can be summarized to conclusions and observations presented below. The challenges that await the spectral method for fatigue life assessment:

- Non-stationary and non-gaussian load processing,
- Mean stress effect correction,
- Material overloading correction.

The areas where this method potentially might be more applicable compared to the time domain methods.

- Vibration fatigue,
- Finite element method- fatigue maps of constructions,
- Fatigue calculations with the use of the strain energy density,
- Fatigue calculations for constructions or materials affected with wind or sea forces.

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