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A TIME DOMAIN FATIGUE PROBLEM TAYLORED INTO FREQUENCY DOMAIN THROUGH AN OPTIMIZATION APPROACH

Raphael Paulino Gonçalves[1], Cícero Ribeiro de Lima[1]

[1]*School of Engineering, Modeling and Applied Social Sciences – UFABC*
Alameda da Universidade, s/n - Anchieta, São Bernardo do Campo - SP, 09606-045, Brazil
raphael.p.goncalves@gmail.com, cicecro.lima@ufabc.com

Abstract. Time domain is the most broadly choice in fatigue testing to completely represent random events, happening in numerous synchronous input channels. The primary disadvantage of this approach is the broad testing span and equipment cost. Time domain-based equipment tests are made from an intricate equipment, which requires servo engines be working to instigate an amount of load at a particular time window. These tests spend a huge time cost, since they require a similar length span of the event that they are repeating, times the necessary reiterations. The frequency domain strategy for fatigue testing requires less intricate equipment, since there is no requirement for servomotors. Moreover, the test length is reduced, since there is no compelling reason to run the full event times the necessary reiterations. The current disadvantage is the limitation to represent random events with different synchronous information channels. Thus, frequency domain tests are mainly applied for basic binary tests, unfit to represent random events. This work aims to introduce another approach that utilizes the fatigue result as input, reversing it to discover the loads that would be required to replicate the result in frequency domain. This can help future developments reducing costs and time required for fatigue testing. Optimization approaches and computations simulations are applied to solve this inverse problem.

Keywords: first keyword, second keyword, third keyword (up to 5 keywords).

1 Introduction

Durability is an extremely important aspect to consider when designing a structure. It ensures its integrity during use, preserving not only the performance aspects itself (whatever they are, depending the nature of the structure), but also the safety of its users and the surroundings. Durability tests can be executed in two different methodologies~~,~~ - frequency-domain and time-domain.

Time domain tests are so called because the load applied to the structure respects this regime. They have a history of loads over a given time window. The load history mimics the loads that the structure would be subjected to during service, and therefore this type of test is the one that best represents the mechanical stresses that the structure would be subjected to in practice.

Tests in the frequency domain are so called because they apply loads to the structure as a function of frequency. The value of the applied loads does not vary, but it depends on how often they occur within a time window. In the frequency domain, the representation of the loads is simplified because the actuators apply the loads to the structure in a binary manner (on/off). In this way, reproducing complex operations, such as vehicle driving at a rough road or a plane under turbulence is only possible by combining different tests, and even then, only with a loss of fidelity to the original.

Unlike the time domain test, where a non-constant load is applied during operation, the frequency domain test has two possible components, the load value and its frequency, which are determined before the test starts and remain constant until the end of the procedure. Different combinations of load value and frequency will give different fatigue results on the structure.

Despite the obvious advantages that time-domain testing has in better representing complex loads, its cost and difficulty in implementation often make it difficult to be applied in practice.

While large companies, such as automotive manufacturers, are able to invest heavily in this type of equipment, smaller companies, such as subcontractors that manufacture parts and components, may not include the purchase and operation of this equipment in their business plan.

The divergence between companies that have time domain testing and those that do not is also a major problem and can cause delays in product development. For example, it is common for an automotive component manufacturer to develop their components with simple frequency domain testing for the reasons mentioned above, and when the component reaches project readiness, it is passed on to the assembler who tests it in your vehicle, but with time domain testing.

Because of the different way each test simulates damage to the structure, different results are obtained between the assembler's and the supplier's tests, requiring a new interaction in development, a redesign of the structure, and a repeat of the tests. It is not uncommon for these interactions to occur several more times. Since fatigue testing in the time domain is extremely time consuming, the repetition of these tests incurs huge additional development costs.

Therefore, the main motivation of this work is to propose a fatigue testing method that can induce the same complex damage in the structure as time domain testing, but in a simple and inexpensive way like frequency domain testing. In addition to the economic advantage of the equipment itself, this new methodology would allow a significant reduction in future product development time, partly by saving testing time and partly by eliminating the many interactions described in the previous paragraph.

The present work aims to introduce and demonstrate the procedure to transform the load history to frequency domain using an optimization process, where the control variable is the stresses or the strains to which the structure is subjected.

This method allows a better control of the result, since the objective of the optimization algorithm depends on the deformation or stress measured in the element (if the study is performed in a finite element model) or the strain gage (if the study is performed on a physical model).

Another advantage of this method is that it allows a complete control of the durability behavior without the need for a loading signal. If the durability behavior is known or there is a predetermined damage target, a sinusoidal loading condition (on-off) can develop that is capable of inducing it.

Finally, the ultimate advantage and goal of this work is to simplify the loads so that they can be used in simple bench tests with binary actuators that can replace time-domain tests.

2 Study setup

2.1 Method to measure stress or strain

The measurement stress or strain in the structure is the central point from which the methodology presented in this paper starts. The stress or deformation amounts, as well as the information about the mechanical behavior of the material, such as the fatigue curves, are used to perform the basic calculations presented later.

The methodology used in this work to estimate the measured data are computer simulations using numerical modeling with the finite element method. This methodology is currently widely used in both industry and academia and can be found in detail in several literatures [1, 2]. This choice is due to its practicality and low cost. It is believed that by means of this numerical method, repeatability of fatigue results can be achieved, which in the end is important for the conclusions as they are compared and therefore any variation coming from the physical fatigue testing procedure has no influence.

Since this is an optimization study where an unknown outcome is sought, it is important that the structure used to develop the methodology does not allow trivial outcomes. In this work, a trivial outcome is one that can be achieved without a complex mathematical approach, as it is either the only solution to the problem or belongs to a universe with few solutions.

To circumvent the trivial results, a structure was developed specifically for this work, as shown in Figure 1.

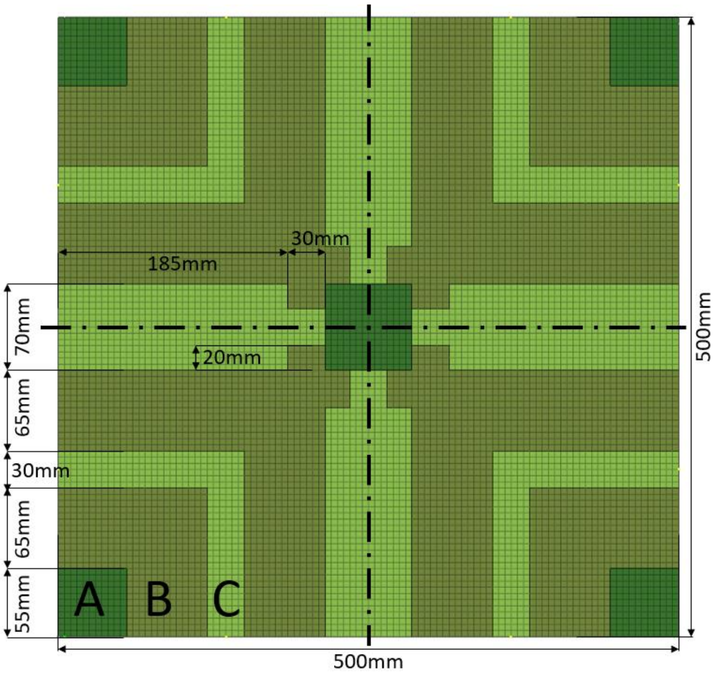


Figure 1 – Details of the structure developed for this study

It is a square ASTM A36 structural steel plate with three different thicknesses, represented by a color and letter code in Figure 1. The darker color zone, represented by the letter A, has a thickness of 6.5 mm, the medium color zone, represented by the letter B, has a thickness of 0.5 mm, and the lighter color zone, represented by the letter C, has a thickness of 0.1 mm. Details of the dimensions of each zone can be seen in Figure 1. The criterion for adopting these thicknesses was to force having negligible values of stress or strain in the zones that support the loads and boundary conditions, represented by the letter A, compared to the zones represented by the letters B and C. The thicknesses of the zones are given in Figure 1. Another criterion considered, although it was not the objective of this work, is that this structure is manufacturable, which could facilitate its reproduction in future studies on the subject.

To solve the problem of triviality of results, the plate developed for this work has intentionally weakened zones with lower thickness and sharp corners (zone C). The thickest zones (Zone A) are dedicated to the boundary conditions (fixed supports) and are therefore strengthened.

2.2 Load conditions

The loads and boundary conditions are applied to the structure can be seen in Figure 2. The central region of the steel plate is subject to constraints in all degrees of freedom. Two force components are applied at each corner, one on the X-axis and the other on the Y-axis. Each of these loads represents an input channel in the system, resulting in a total of eight input channels. These channels are subject to random variation in their intensity over time.

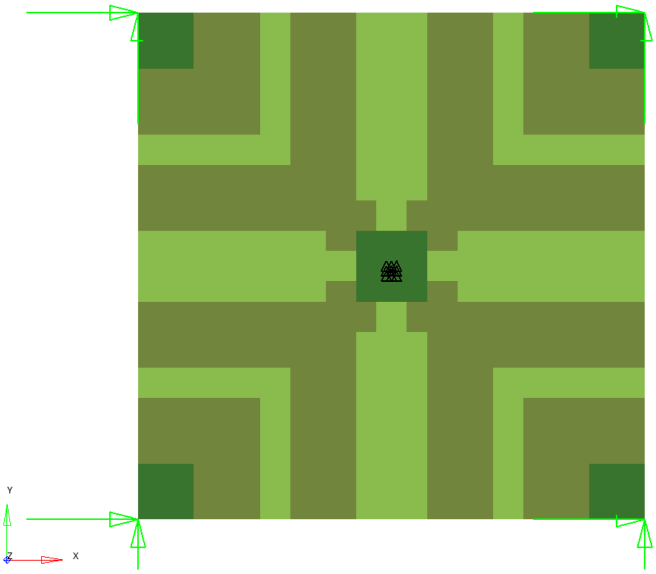


Figure 2 – Loads and boundary conditions on the structure

The maximum and minimum values for tension and compression were chosen so that the structure is never subjected to a load that induces a stress above the yield strength and therefore, fatigue regime is expected to be high cycle [3].

As stated before, it is important to ensure that there are no trivial results when developing this method.

Figure 3 shows four fatigue results in the same structure, where in each case the eight input channels have different values, each determined randomly, as can be seen in Figure 4.

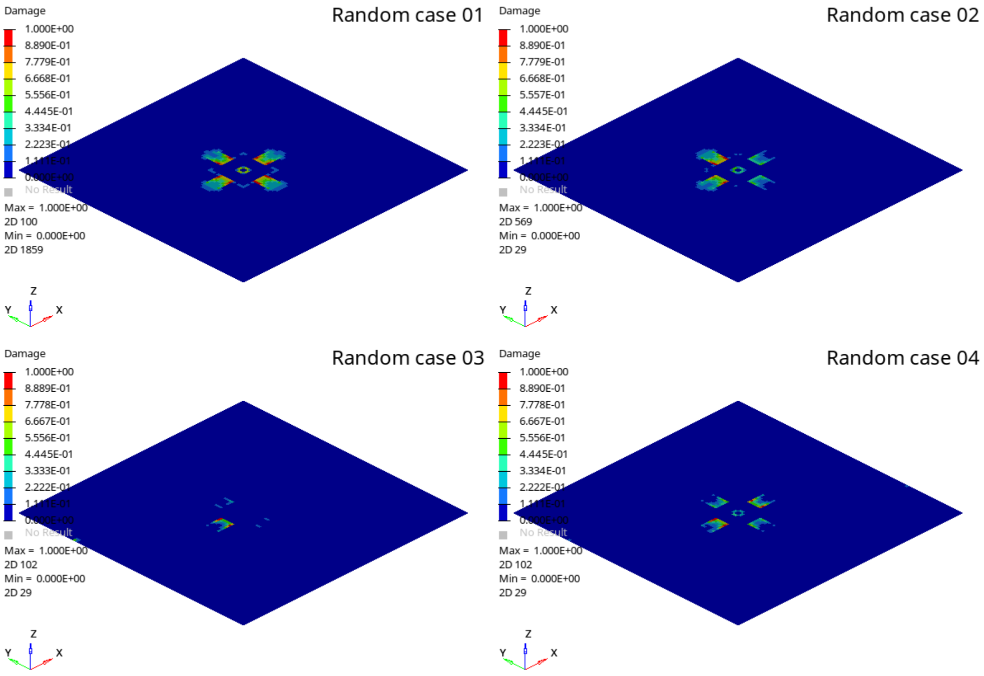


Figure 3 - Different damage results for different random loads application at the input channels.

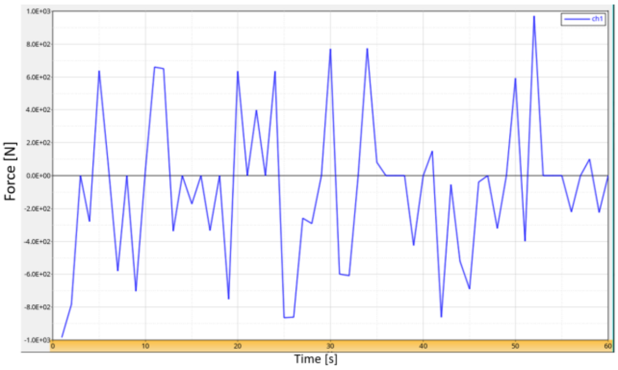


Figure 4 - Random signal used in channel 1 of case 1. Each channel and in each case the curves are different and generated randomly.

3 The optimization methodology

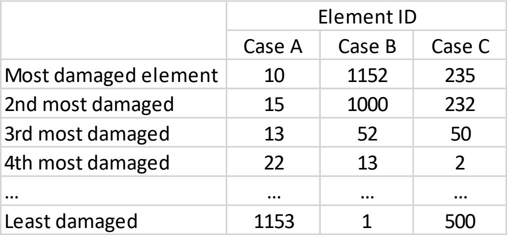
3.1 The objective function

A fatigue result of a structure is the determination of when and where a structure will present mechanical failure after a cyclic load application. In a physical test, this is achieved observing the occurrence of mechanical failure during the test. In a finite element model, the result is given in each element in terms of life or damage, where one is the inverse of the other.

As seen in

Figure 3, red areas mean more damage and therefore, mechanical failure is expected to happen first than of the blue areas, which represent less damage or even zero damage. What differentiates each of the four results on

Figure 3 is where and when each element indicates the mechanical failure will occur, given by the order of them. In this sense, different fatigue results, generated by different load conditions, will display different element ordering. Results ordering examples for hypothetical cases can be seen below on Figure 5. This is the key point concept proposed by the methodology here, determine the element ordering using the damage or life results in each element.



	Element ID		
	Case A	Case B	Case C
Most damaged element	10	1152	235
2nd most damaged	15	1000	232
3rd most damaged	13	52	50
4th most damaged	22	13	2
…	…	…	…
Least damaged	1153	1	500

Figure 5 – Different fatigue results will display different element ordering. Cases A, B and C are hypothetical, just to explain element ordering in fatigue results.

To achieve this ordering of damage results in each element, the objective function considers the stress and strain instead of the damage or life itself. The reason for this is that the relationship between load (which is the input variable to the system) and fatigue is not linear. Although the specific relationship can vary depending of several existent calculations strategies as can be seen in [3] and [4], such as strain-life approach or stress-life approach, this relationship is always exponential. This exponential relationship adds another degree of difficulty to the optimization that makes the process unfeasible. By the other hand, the relationship between loads and stress or strains are linear, given by Hooke´s law:

$$KU = \mathrm{F} \tag{1}$$

Although without exponentiality, if the ordering of results of stress and strain is guaranteed, the ordering of damage and life results in each element is guaranteed as well. To achieve this ordering, the proposal of this work starts from the idea of maximization of the sum of the differences of stresses or strains results between each element in the ordering target as seen below:

$$\frac{(\varepsilon_{1md} - \varepsilon_{2md})}{abs(\varepsilon_{1md} - \varepsilon_{2md})} + \frac{(\varepsilon_{2md} - \varepsilon_{3md})}{abs(\varepsilon_{2md} - \varepsilon_{3md})} + \frac{(\varepsilon_{3md} - \varepsilon_{4md})}{abs(\varepsilon_{2md} - \varepsilon_{3md})} + \cdots + \frac{(\varepsilon_{N-1md} - \varepsilon_{Nmd})}{abs(\varepsilon_{N-1md} - \varepsilon_{Nmd})} \tag{2}$$

The method explained here works for both stress or strain if the model is linear and working inside the elastic limit behavior. For the purpose to simplify the notation, all formulas will show the strain symbol. The notations "1md", "2md", …, "Nmd", indicate the strain results for the most damaged element, second most damaged respectively until the strain of the least damaged element, represented by "Nmd".

Each term can only return two values, +1 and -1. In case of the target ordering condition is satisfied, the term returns +1 and in case not, it returns -1. The more conditions satisfied, the more will be the positive terms and therefore, maximizing the global sum leads to a desirable value.

However, summing only the differences between adjacent values are not sufficient to characterize the system. For instance, if in a hypothetical scenario, the latest damaged element presents the highest strain or stress value during an interaction, its related term will return -1 to the global sum. The optimization may converge with a high function value but at the end, the fatigue result will be totally different, since the most damaged element will be the one that should present the least damage.

To solve this, each element result must be compared to each other and not only to its adjacent, as can be seen in Table 1:

Table 1 – Comparison of each element strain result with all other elements in the model.

	ε_{1md}	ε_{2md}	ε_{3md}	ε_{4md}	…	ε_{N-1md}
ε_{1md}					…	
ε_{2md}	$\frac{(\varepsilon_{1md} - \varepsilon_{2md})}{abs(\varepsilon_{1md} - \varepsilon_{2md})}$				…	
ε_{3md}	$\frac{(\varepsilon_{1md} - \varepsilon_{3md})}{abs(\varepsilon_{1md} - \varepsilon_{3md})}$	$\frac{(\varepsilon_{2md} - \varepsilon_{3md})}{abs(\varepsilon_{2md} - \varepsilon_{3md})}$			…	
ε_{4md}	$\frac{(\varepsilon_{1md} - \varepsilon_{4md})}{abs(\varepsilon_{1md} - \varepsilon_{4md})}$	$\frac{(\varepsilon_{2md} - \varepsilon_{4md})}{abs(\varepsilon_{2md} - \varepsilon_{4md})}$	$\frac{(\varepsilon_{3md} - \varepsilon_{4md})}{abs(\varepsilon_{3md} - \varepsilon_{4md})}$		…	
…	…	…	…	…	…	…
ε_{Nmd}	$\frac{(\varepsilon_{1md} - \varepsilon_{Nmd})}{abs(\varepsilon_{1md} - \varepsilon_{Nmd})}$	$\frac{(\varepsilon_{2md} - \varepsilon_{Nmd})}{abs(\varepsilon_{2md} - \varepsilon_{Nmd})}$	$\frac{(\varepsilon_{3md} - \varepsilon_{Nmd})}{abs(\varepsilon_{3md} - \varepsilon_{Nmd})}$	$\frac{(\varepsilon_{4md} - \varepsilon_{Nmd})}{abs(\varepsilon_{4md} - \varepsilon_{Nmd})}$	…	$\frac{(\varepsilon_{N-1md} - \varepsilon_{Nmd})}{abs(\varepsilon_{N-1md} - \varepsilon_{Nmd})}$

Then, as in (2), all terms must be summed and the optimizer will work to maximize the function. Although the sum of all terms presented in Table 1 is the base of the methodology of this work and its useful to display how far from the target the optimizer is, by itself it is insufficient to guide the optimizer to the best answer. By "best", it is important to specify that the least damaged elements remain with the lowest values for stress and strain and at the same time, the most damaged elements remain with the highest values for stress and strain as a priority, otherwise even when close to 100% of the target, it is still possible to observe zones should not have damage with damage or even with more damage than other zones.

The solution is to apply a weight at each term depending of its location on the order, as can be seen Table 2:

Table 2 - Comparison of each element strain result with all other elements in the model with weight

WEIGHT		N^2	$(N-1)^2$	$(N-2)^2$	$(N-3)^2$		2^2
		ε_{1md}	ε_{2md}	ε_{3md}	ε_{4md}	…	ε_{N-1md}
1	ε_{1md}					…	
2^2	ε_{2md}	$\frac{(\varepsilon_{1md}-\varepsilon_{2md})}{abs(\varepsilon_{1md}-\varepsilon_{2md})}*1*N^2$				…	
3^2	ε_{3md}	$\frac{(\varepsilon_{1md}-\varepsilon_{3md})}{abs(\varepsilon_{1md}-\varepsilon_{3md})}*2^2*N^2$	$\frac{(\varepsilon_{2md}-\varepsilon_{3md})}{abs(\varepsilon_{2md}-\varepsilon_{3md})}*2^2*(N-1)^2$			…	
4^2	ε_{4md}	$\frac{(\varepsilon_{1md}-\varepsilon_{4md})}{abs(\varepsilon_{1md}-\varepsilon_{4md})}*3^2*N^2$	$\frac{(\varepsilon_{2md}-\varepsilon_{4md})}{abs(\varepsilon_{2md}-\varepsilon_{4md})}*3^2*(N-1)^2$	$\frac{(\varepsilon_{3md}-\varepsilon_{4md})}{abs(\varepsilon_{3md}-\varepsilon_{4md})}*3^2*(N-2)^2$		…	
…	…	…	…	…	…	…	…
N^2	ε_{Nmd}	$\frac{(\varepsilon_{1md}-\varepsilon_{Nmd})}{abs(\varepsilon_{1md}-\varepsilon_{Nmd})}*N^2*N^2$	$\frac{(\varepsilon_{2md}-\varepsilon_{Nmd})}{abs(\varepsilon_{2md}-\varepsilon_{Nmd})}*N^2*(N-1)^2$	$\frac{(\varepsilon_{3md}-\varepsilon_{Nmd})}{abs(\varepsilon_{3md}-\varepsilon_{Nmd})}*N^2*(N-2)^2$	$\frac{(\varepsilon_{4md}-\varepsilon_{Nmd})}{abs(\varepsilon_{4md}-\varepsilon_{Nmd})}*N^2*(N-3)^2$	…	$\frac{(\varepsilon_{N-1md}-\varepsilon_{Nmd})}{abs(\varepsilon_{N-1md}-\varepsilon_{Nmd})}*N^2*2^2$

When a load is applied to a finite element model, all elements will display a stress and strain results, regardless the magnitude of this load. The same does not occur to fatigue damage. Due to the already mentioned exponential relationship, infinite life can be achieved and therefore no damage value is returned (zero damage). When more than one element presents zero damage, it is not possible to impose an order to stress and strain results and doing it empirically, may induce the optimizer to achieve undesirable results. The solution is to treat all zero elements with the same weight in the sum, as if all were the "N" element of the series. Table 3 exemplifies this for a hypothetical scenario where the last three elements have zero damage:

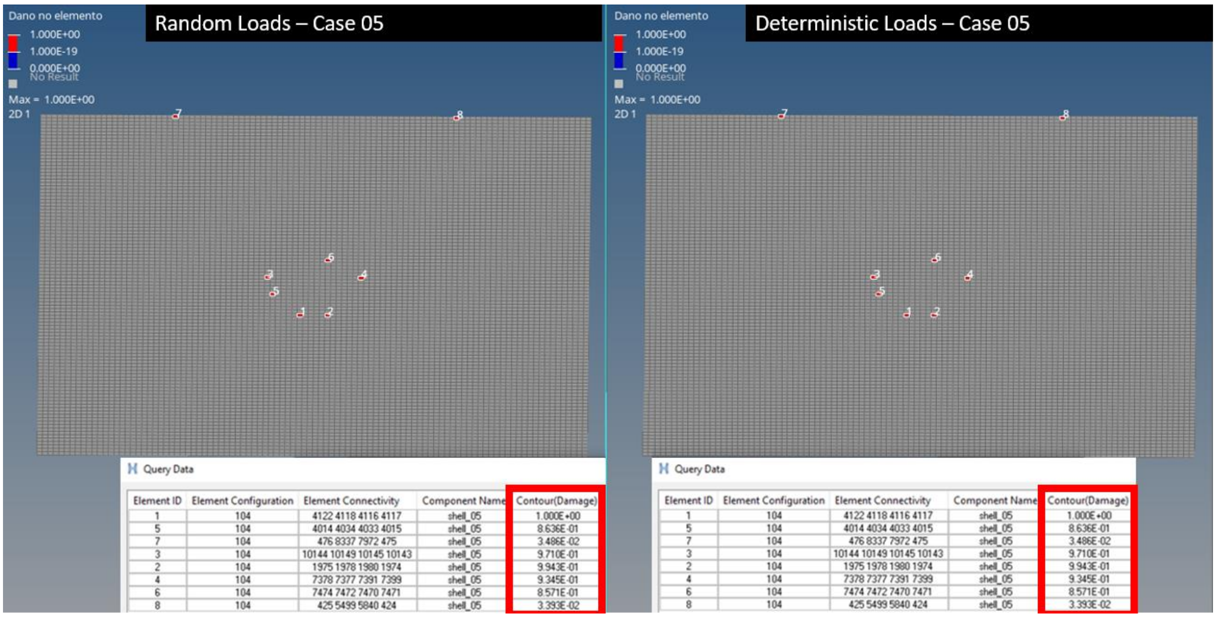
Table 3 – Hypothetical scenario where the three least damaged elements have zero damage

WEIGHT		N^2	…	4^2	3^2	2^2	1
		ε_{1md}	…	ε_{N-3md}	ε_{N-2md}	ε_{N-1md}	ε_{Nmd}
1	ε_{1md}		…				
2^2	ε_{2md}	$\frac{(\varepsilon_{1md}-\varepsilon_{2md})}{abs(\varepsilon_{1md}-\varepsilon_{2md})}*1*N^2$	…				
…	…	…	…	…	…	…	…
$(N-3)^2$	ε_{N-3md}	$\frac{(\varepsilon_{1md}-\varepsilon_{N-3md})}{abs(\varepsilon_{1md}-\varepsilon_{N-3md})}*(N-3)^2*N^2$	…				
$(N-2)^2$	ε_{N-2md}	$\frac{(\varepsilon_{1md}-\varepsilon_{N-2md})}{abs(\varepsilon_{1md}-\varepsilon_{N-2md})}*(N-2)^2*N^2$	…	$\frac{(\varepsilon_{N-3md}-\varepsilon_{N-2md})}{abs(\varepsilon_{N-3md}-\varepsilon_{N-2md})}*(N-2)^2*4^2$			
$(N-2)^2$	ε_{N-1md}	$\frac{(\varepsilon_{1md}-\varepsilon_{N-1md})}{abs(\varepsilon_{1md}-\varepsilon_{N-1md})}*(N-2)^2*N^2$	…	$\frac{(\varepsilon_{N-3md}-\varepsilon_{N-1md})}{abs(\varepsilon_{N-3md}-\varepsilon_{N-1md})}*(N-2)^2*4^2$	0		
$(N-2)^2$	ε_{Nmd}	$\frac{(\varepsilon_{1md}-\varepsilon_{Nmd})}{abs(\varepsilon_{1md}-\varepsilon_{Nmd})}*(N-2)^2*N^2$	…	$\frac{(\varepsilon_{N-3md}-\varepsilon_{Nmd})}{abs(\varepsilon_{N-3md}-\varepsilon_{Nmd})}*(N-2)^2*4^2$	0	0	

3.2 Size of the optimization problem

The more elements to be considered as strain or stress results and to be added to the Table 2, the better to characterize the system, however, this might increase the formulation complexity of the function in a level that, depending of the software to be used, became unfeasible to perform the optimization. In Hyperstudy (the software used for this work) for example, there is a limitation into the number of characters of the formulas and to consider all elements of the model, 10000 elements in this study, it is not possible.

However, considering a low number of elements might not be enough to characterize the system, which can lead to an indetermination, where more than one answer satisfies the problem, not reaching the proposed objective, as can be seen in Figure 6 andFigure 7.



Element ID	Element Configuration	Element Connectivity	Component Name	Contour(Damage)
1	104	4122 4118 4116 4117	shell_05	1.000E+00
5	104	4014 4034 4033 4015	shell_05	8.636E-01
7	104	476 8337 7972 475	shell_05	3.486E-02
3	104	10144 10149 10145 10143	shell_05	9.710E-01
2	104	1975 1978 1980 1974	shell_05	9.943E-01
4	104	7378 7377 7391 7399	shell_05	9.345E-01
6	104	7474 7472 7470 7471	shell_05	8.571E-01
8	104	425 5499 5840 424	shell_05	3.393E-02

Element ID	Element Configuration	Element Connectivity	Component Name	Contour(Damage)
1	104	4122 4118 4116 4117	shell_05	1.000E+00
5	104	4014 4034 4033 4015	shell_05	8.636E-01
7	104	476 8337 7972 475	shell_05	3.486E-02
3	104	10144 10149 10145 10143	shell_05	9.710E-01
2	104	1975 1978 1980 1974	shell_05	9.943E-01
4	104	7378 7377 7391 7399	shell_05	9.345E-01
6	104	7474 7472 7470 7471	shell_05	8.571E-01
8	104	425 5499 5840 424	shell_05	3.393E-02

Figure 6 – Fatigue results comparison between Random and Deterministic loads (frequency domain – optimization results) for case 05. The result plot is applied only at the 8 elements considered on the objective function. Note that the two images seem to be equal since results and element IDs are the same but are actually two distinct results.

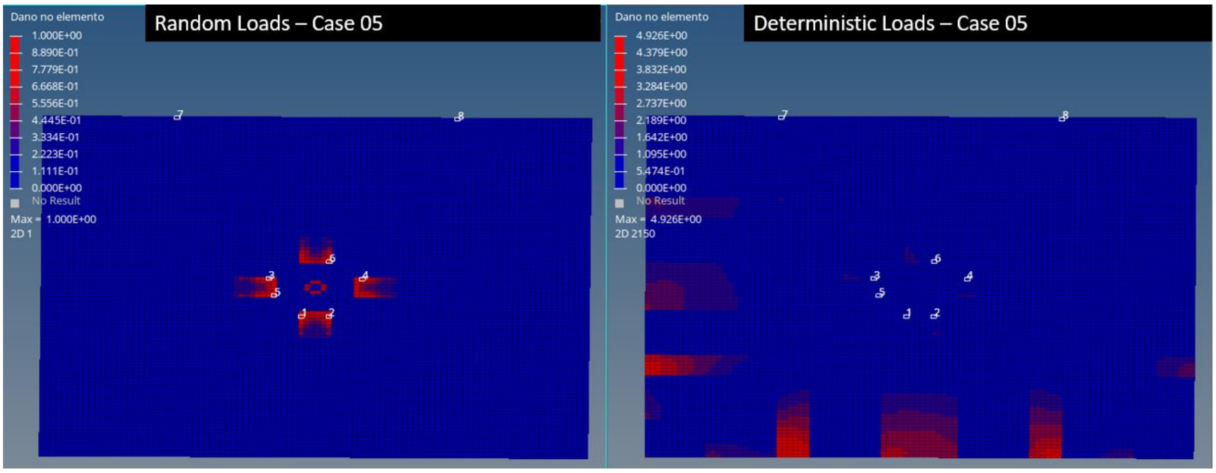


Figure 7 - Fatigue results comparison between Random and Deterministic loads (frequency domain – optimization results) for case 05. The result plot is applied in all the model.

As can be observed, when considering a low number of elements, eight in this illustrative example, the optimizer is able to converge and satisfies the condition where element has a greater damage than element 2, which has a greater element then element 3 and so on, until element 8, which is the least damaged. When the simulation results are contrasted to the original random case, considering only the eight elements, both present the same damage results. However, when plotting the damage in all the model, it is possible to see that both structures have completely different fatigue performances and although the optimizer achieved a perfect solution, the number of elements chosen to characterize the system was insufficient.

The solution proposed by this work, is to select a reasonable number of elements that could be able to characterize the structure, capturing all spots of stress concentration of the model. In the case of the model of this work, 56 elements were chosen, capturing the sharp corners of the area with the lowest thickness. Details of these chosen elements can be seen in Figure 8.

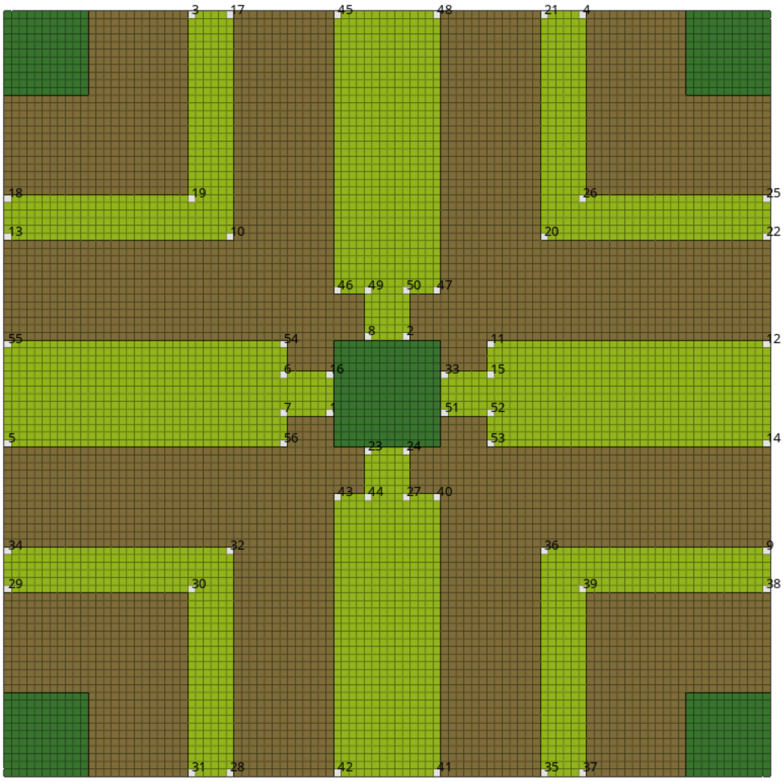


Figure 8 – Details of the 56 elements chosen to be included into the objective function

3.3 Operation frequency of the loads

As a result of the process, the optimization algorithm will determine a specific load vector for each channel of the structure, replacing the random signal. Instead of a time history of loads, these vectors will act on the structure in a binary mode (on and off) at a given frequency. This frequency cannot be grater than the first normal mode of the structure, when constrained in the same way of the operational condition. In the model considered for this study, the first normal mode is ~1.732Hz as can be seen on Figure 9.

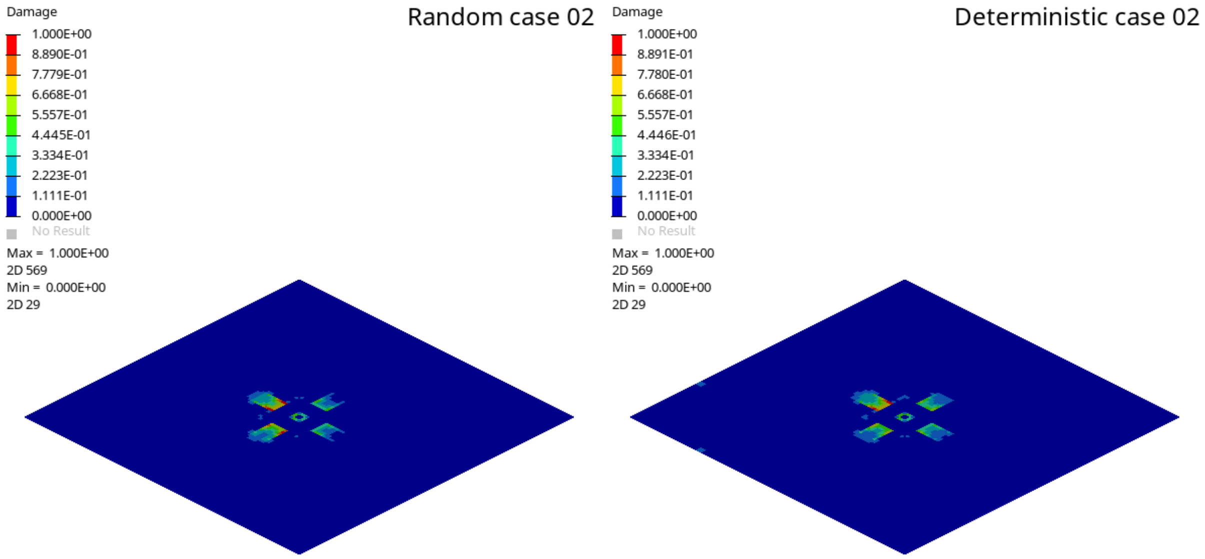
Figure 9 – First normal mode of the structure, considering same boundary conditions as the operational cases

The reason for this is to avoid that the loading condition to be applied by the vectors excites the structure into a point that the structure is no more considered under static condition [5]. When the structure is submitted a dynamic loading condition, its inertia becomes relevant into the system, producing a different response to a pure linear system that is exclusively under the domain stablished by (3).

4 Case study – 4 random cases

The following examples to be demonstrated here utilize the genetic algorithm at HyperStudy, part of Altair package. Altair has an extensive documentation with explanation of how each of the optimization algorithms work in HyperStudy and can be checked in [4]. Although the relationship between load, stresses and strains are linear, the relationship between the load and the order of the results, as explained in previous section, is extremely nonlinear. In this sense, algorithms that are not able to find global maximum values are unable to find good results in our tests. For this reason, the genetic algorithm was adopted in this work.

The optimization process was applied in four cases, which in each one of them, the structure was submitted to a set of random loads in eight channels as seen in Figure 2. These loads are randomly varied along 60 seconds as seen in Figure 4. The comparison of damage results, between the cases generated randomly and its counterparts generated by the optimization process can be checked below in Figure 10, Figure 11, Figure 12 and Figure 13.



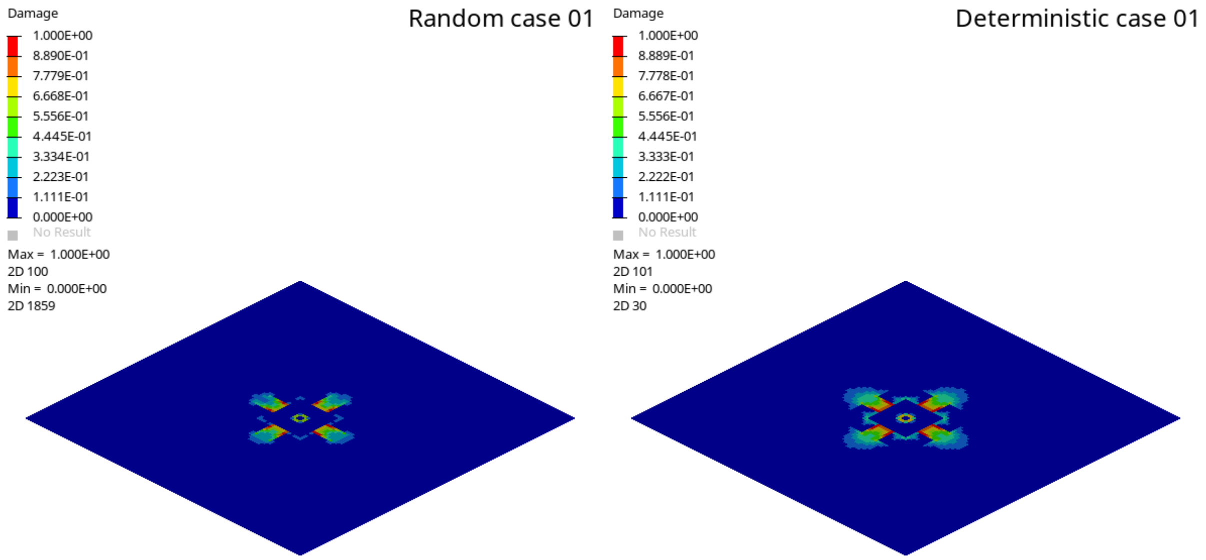


Figure 10 – Comparison results: Random case 01 vs Deterministic version in frequency domain, created by the optimization process

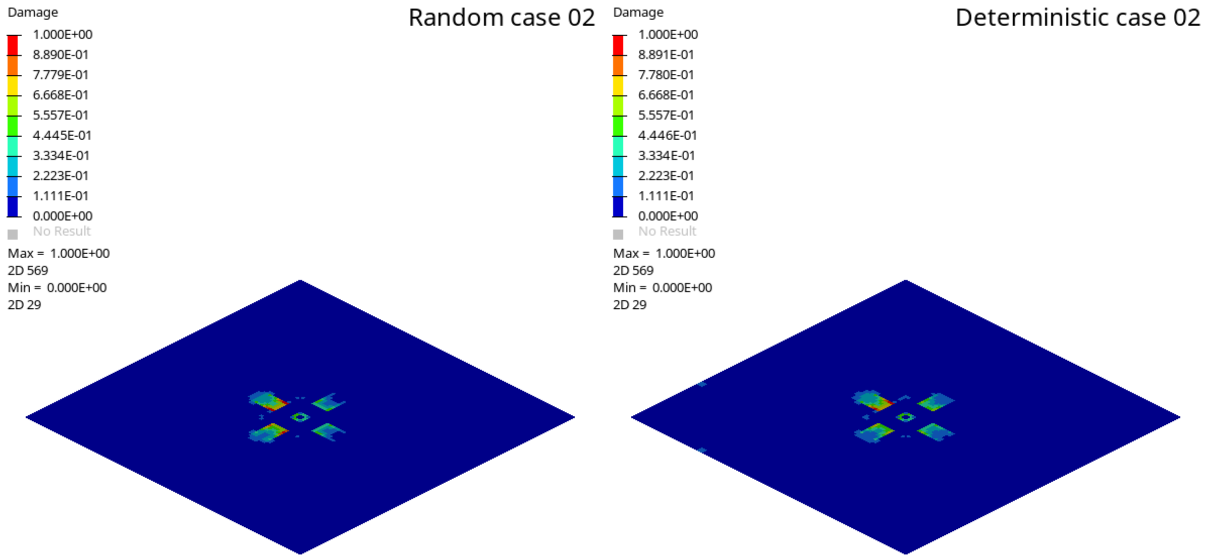


Figure 11 – Comparison results: Random case 02 vs Deterministic version in frequency domain, created by the optimization process

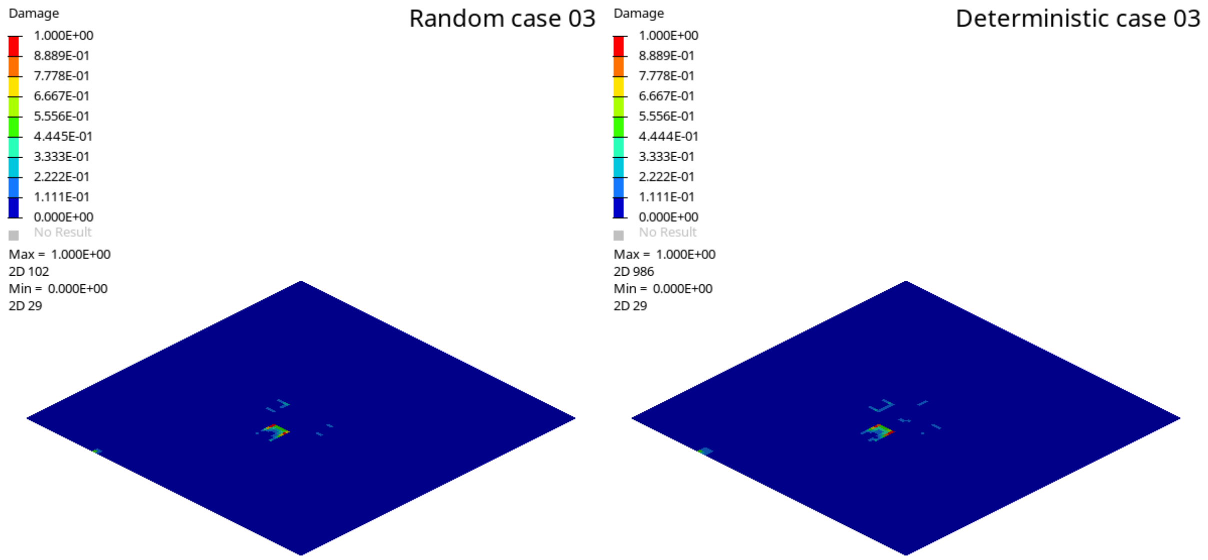


Figure 12 – Comparison results: Random case 03 vs Deterministic version in frequency domain, created by the optimization process

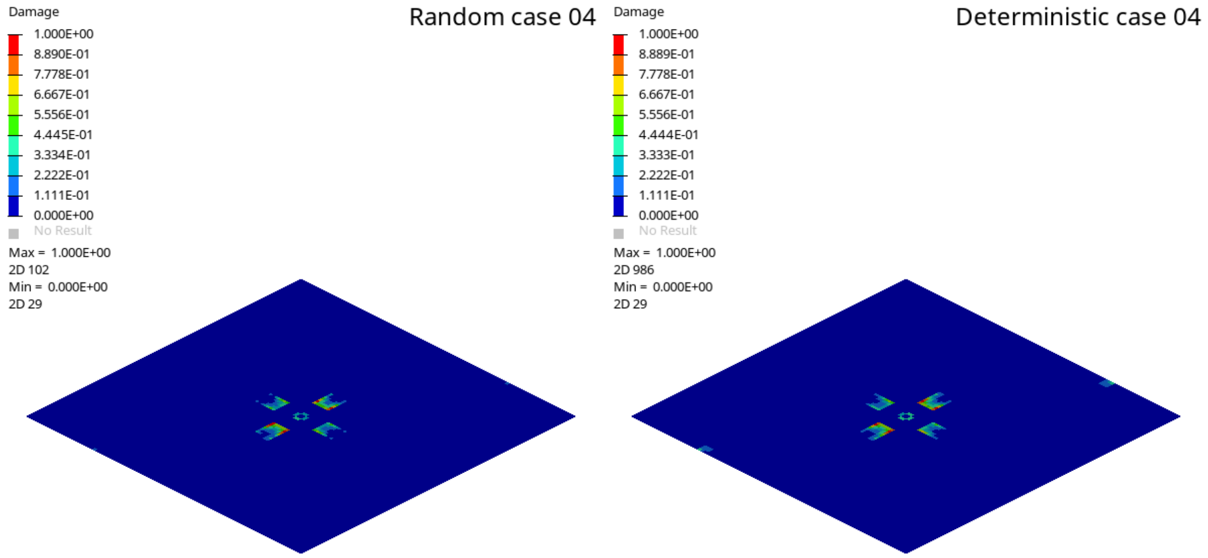
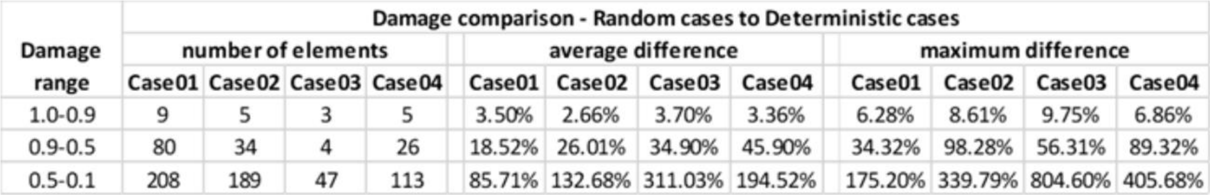


Figure 13 – Comparison results: Random case 04 vs Deterministic version in frequency domain, created by the optimization process

The comparison using the graphic plot for the fatigue damage shows that the optimization strategy proposed in this work is able to find a set of deterministic loads in each of the eight channels that can induce a similar fatigue performance. Table 4 provides a more detailed contrast, comparing the results element to element in both methodologies. The comparison seen in the Table 4 is grouped by damage ranges to allow a better comprehension of the results. The lower the damage, the lower is the damage correlation due to the exponential relationship between stress (or strain) and damage [3] [4].

Table 4 – Damage comparison between random cases to deterministic cases – element to element



Damage range	Damage comparison - Random cases to Deterministic cases											
	number of elements				average difference				maximum difference			
	Case01	Case02	Case03	Case04	Case01	Case02	Case03	Case04	Case01	Case02	Case03	Case04
1.0-0.9	9	5	3	5	3.50%	2.66%	3.70%	3.36%	6.28%	8.61%	9.75%	6.86%
0.9-0.5	80	34	4	26	18.52%	26.01%	34.90%	45.90%	34.32%	98.28%	56.31%	89.32%
0.5-0.1	208	189	47	113	85.71%	132.68%	311.03%	194.52%	175.20%	339.79%	804.60%	405.68%

Another important comparison is the time reduction in testing. In random test events, the amount of damage occurring at a given time window is not constant and may time slots with zero or almost zero damage may occur. Also, the time event must respect the time window, since increasing the test speed means by definition, changing completely the time signal. Frequency domain test by the other hand, induces a constant amount of damage in each repetition and the execution speed can be increased until the edge of the first normal mode. The time comparison among all cases can be seen in Table 5.

Table 5 - Time comparison to complete a test between random cases and deterministic cases

	Random test in time domain						Deterministic test in frequency domain			
	Case01	Case02	Case03	Case04			Case01	Case02	Case03	Case04
Time event [s]	60	60	60	60		execution frequency [Hz]	1.7	1.7	1.7	1.7
Repetitions	3831.42	4995.01	171821	67470		Repetitions	3831.42	24650	412317	297650
Total Time [h]	63.9	83.3	2863.7	1124.5		Total Time [h]	0.6	4.0	67.4	48.6
Total Time [d]	2.7	3.5	119.3	46.9		Total Time [d]	0.0	0.2	2.8	2.0

5 Conclusions

The methodology presented in this work was able to create a set of deterministic loads, working in binary mode (on / off) at a determined frequency which can reproduce the same fatigue behavior in a structure compared to a traditional random load condition. The results shown a correlation in damage around 3.7% to damage area from 1 to 0.9 damage and 46% from 0.9 to 0.5 damage area.

The time reduction in test execution is also a good benefit from this methodology. One of the cases shown a potential to reduce almost four months of testing. Although this time saving is not linear and each case presented big differences among each other, a good reduction was observed in all of them.

A future study may include the dynamic behavior of the system. This could allow not only achieve better correlations for structures known to be working in a dynamic environment, and also, allow the test to be executed in frequencies beyond the first normal mode of the structure.

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