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# Effects of Forces and Material Types on Fatigue Analysis of Beams

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**Abstract**

This numerical and statistical study deals with the evaluate the effects of forces and material types on safety factor and equivalent alternating stress of beams made of metal materials. Numerical calculations were performed by using ANSYS Workbench software. Design of analyzes based on different determining factors was determined utilizing Taguchi L9 orthogonal array design consisting of two determining factors consisting of three levels. The first and second determining factors were chosen as applied force and material type, respectively. In the finite element modeling, beams with clamped-free boundary conditions were considered. Determination of optimal levels of all factors was found using signal-to-noise ratio analysis. The contribution rate and significance level of all determining factors on the safety factor and equivalent alternating stress were calculated utilizing analysis of variance. According to the results calculated from this study, the optimum results for safety factor and equivalent alternating stress of beams were obtained by using the first levels of all determining factors. While the increase in the applied force values causes a decrease in the safety factor, it leads to an increase in the equivalent alternating stress.

**Keywords:** Safety factor, Material, Beam, ANSYS, Taguchi method.

## 1. Introduction

Fatigue may occur in the material under continuous loads. Depending on the number of applied loads, small cracks in the material may grow and then the small cracks can cause major damage. Metal materials can exhibit different fatigue life depending on their geometric structures and the magnitude of the applied force. Therefore, it is significant to determine the fatigue life of metal materials used in many sectors, especially in the field of mechanical engineering. Fatigue analysis, which has a very important in the field of engineering, has been examined in many studies [1-7] depending on different sectors. Many theories and models were offered to estimate the fatigue life and damage [8-18]. In this literature review, a lot of studies have been carried out on fatigue analysis. The effects of the methods used in the production of the bellows used in air suspension systems on the product quality were evaluated and their mechanical properties were examined [19]. A review study on the fatigue life of crankshafts under different loads is presented and the application areas of finite elements and experimental methods are discussed [20]. The fatigue analysis of the wheels designed according to aluminum material was evaluated and they benefited from ANSYS software in their studies. They also used different radial loads [21]. The fatigue analysis of the rail connecting rods was investigated using ANSYS software, which includes the finite element method [22]. Fatigue analysis of spur gears under different loadings was performed and finite element method was used. In addition, different analyzes were examined using the finite element method [23]. In another study, the fatigue life analysis for steam turbine blades was investigated using linear and elastic finite element methods [24]. In this study, unlike the existing studies in the literature, finite element and Taguchi methods were used to safety factor and equivalent alternating stress of beams made of metal materials. This study focuses on evaluating the impact of forces and material types on the safety factor and equivalent alternating stress of metal beams. The numerical approaches were determined by the ANSYS Workbench software. The analysis design was determined using the Taguchi L9 orthogonal array design, which involved two determining factors with three levels each. The first determining factor represents the applied force, while the second determining factor represents the material type. The finite element modeling was considered for beams with clamped-free boundary conditions.

## 2. Materials and Methods

In the study, three different metal materials were used. These materials were chosen as Structural Steel, Aluminum Alloy, and Magnesium (AM100A, cast, T6), respectively. Each metal material has various mechanical properties and density. The general properties of the metal materials were demonstrated in Table 2.

**Table 1.** Common Material Properties [25]

| Properties | Structural Steel | Aluminum Alloy | Magnesium, AM100A, T6 |
|---|---|---|---|
| **Density** | 7850 kg/m³ | 2770 kg/m³ | 1802 kg/m³ |
| **Young's Modulus** | 200 GPa | 71 GPa | 46.14 GPa |
| **Tensile Yield Strength** | 250 MPa | 280 MPa | 118.4 MPa |
| **Tensile Ultimate Strength** | 460 MPa | 310 MPa | 175.1 MPa |

Finite element calculations were performed using the L9 orthogonal array. This array was used based on the Taguchi method. In this design, there are two determining factors and each determining factor consists of three different levels. The first determining factor selected was the force applied at the free end of the beams, followed by the material type, which was chosen as the second factor. The determining factors used in the analyzes and levels of these factors are given in Table 2.

**Table 2.** Determining factors and levels

| Factor | Code | Levels | | |
|---|---|---|---|---|
| | | **Level 1** | **Level 2** | **Level 3** |
| **Force** | A | 1N | 2N | 3N |
| **Material Type** | B | Structural Steel | Aluminum Alloy | Magnesium, AM100A, T6 |

In this study, safety factor and equivalent alternating stress were preferred as the responses. The optimum value for the safety factor and equivalent alternating stress was considered as the maximum and minimum result, respectively. In this context, "the smaller is better" and "the larger is better" quality characteristics in the Taguchi method were utilized. These quality characteristics for "the smaller is better" and "the larger is better" were given in Equation 1 and Equation 2 [26], respectively.

$$(S/N)_{SB} \text{ for } \sigma = -10.\log\left(n^{-1}\sum_{i=1}^{n}(y_i)^2\right) \quad \textbf{(1)}$$

$$(S/N)_{HB} \text{ for } \mu = -10.\log\left(n^{-1}\sum_{i=1}^{n}(y_i^2)^{-1}\right) \quad \textbf{(2)}$$

In these equations, n signifies the number of numerical calculations for a trial and $y_i$ is $i^{th}$ result identified. Signal to Noise (S/N) ratios based on numerical repossess were calculated using Equation 1 and Equation 2. Statistical analysis, graphics and figures based on this analysis were obtained using Minitab R15 program. Besides of that, analysis of variance was performed at 95 % confidence level.

## 3. Finite Element Analysis

Finite element examines were completed utilizing ANSYS Workbench software. The cross-sectional dimensions of beams were chosen as 2 mm x 20 mm. In addition, the beam length was determined as 200 mm. Each beam was examined under the clamped-free (C-F) boundary conditions. In mesh operation, element order was determined as quadratic. Element size was determined as 0.5. Thus, 64000 elements and 310169 nodes were used in the numerical analyses. Equivalent (von-Mises) was utilized as stress component. The forces were applied to the free end of the beams. Stress life was determined as analysis type. Design life was used as $10^9$ and all bodies of beams were assumed as geometry. Also, scale factor was utilized as 1. Mean stress correction theory for safety factor and equivalent alternating stress of beams were performed in accordance with Soderberg. Constant amplitude load fully reversed and means stress correction theory were illustrated in Figure 1.

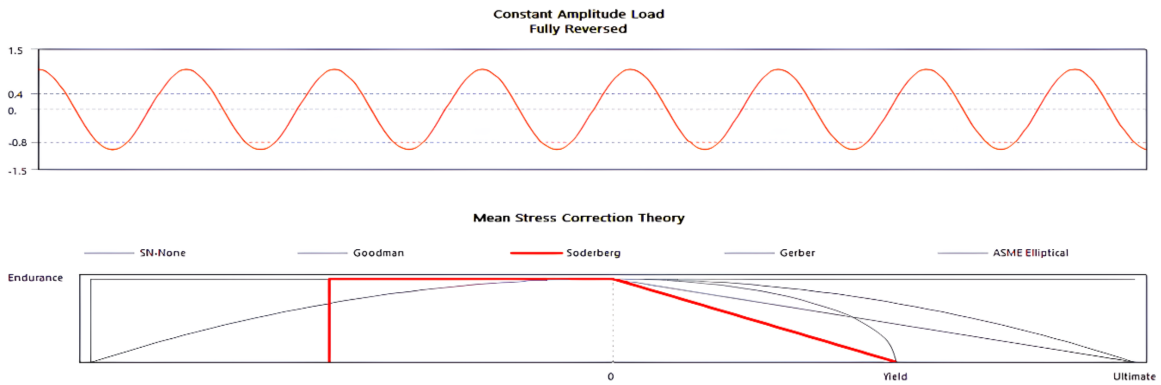


**Figure 1.** Constant amplitude load fully reversed and means stress correction theory [25]

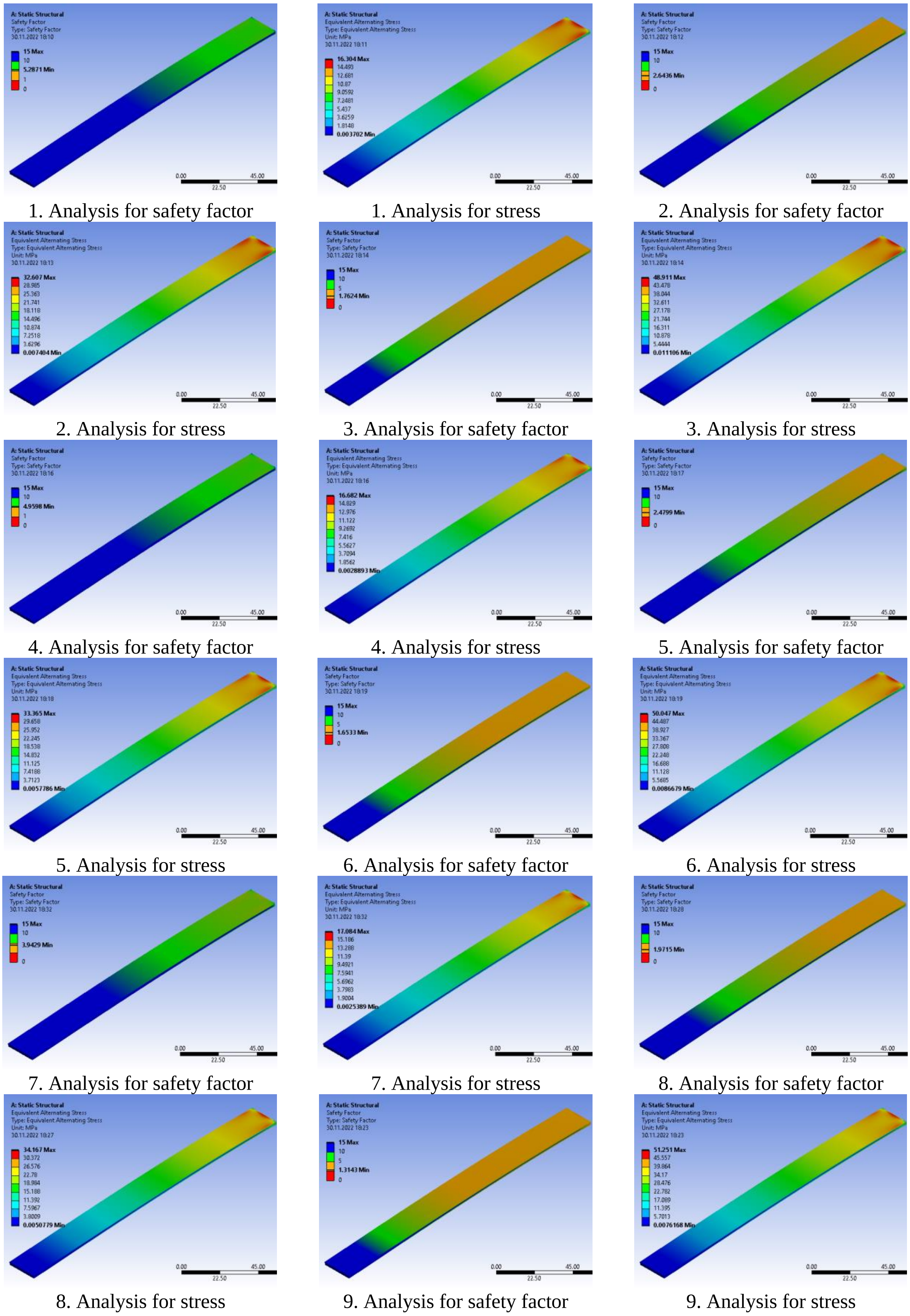


**Figure 2.** Numerical results for L9 orthogonal array

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## 4. Results and Discussions

This numerical and statistical research paper deals with the evaluate the effect of forces and material types on safety factor (μ) and equivalent alternating stress (σ) of beams under clamped-free boundary conditions utilizing finite element and Taguchi approaches. Finite element and S/N ratio results were indicated in Table 3. It shows that overall means for safety factor and equivalent alternating stress in accordance with Taguchi L9 orthogonal array were found as $\overline{T_{\mu}} = 2.8905$ and $\overline{T_{\sigma}} = 33.3798$ MPa, respectively.

As seen in Figure 2, while the red regions are the most affected parts, the least affected parts are the blue regions.

To select the significance of force and material type towards on safety factor and equivalent alternating stress, analysis of variance (ANOVA) was implemented in accordance with 95 % confidence level. The results were tabled in Table 4.

**Table 3.** Finite element and S/N results

| No | Variables | | Results | | | |
|---|---|---|---|---|---|---|
| | A | B | Safety Factor μ (-) | S/N η (dB) | Equivalent Alternating Stress σ (MPa) | S/N η (dB) |
| 1 | $A_1$ | $B_1$ | 5.2871 | 14.4644 | 16.3040 | -24.2459 |
| 2 | $A_1$ | $B_2$ | 2.6436 | 8.4439 | 32.6070 | -30.2662 |
| 3 | $A_1$ | $B_3$ | 1.7624 | 4.9221 | 48.9110 | -33.7881 |
| 4 | $A_2$ | $B_1$ | 4.9598 | 13.9093 | 16.6820 | -24.4450 |
| 5 | $A_2$ | $B_2$ | 2.4799 | 7.8887 | 33.3650 | -30.4658 |
| 6 | $A_2$ | $B_3$ | 1.6533 | 4.3670 | 50.0470 | -33.9876 |
| 7 | $A_3$ | $B_1$ | 3.9429 | 11.9163 | 17.0840 | -24.6518 |
| 8 | $A_3$ | $B_2$ | 1.9715 | 5.8959 | 34.1670 | -30.6721 |
| 9 | $A_3$ | $B_3$ | 1.3143 | 2.3739 | 51.2510 | -34.1940 |
| | Overall Means | | 2.8905 | - | 33.3798 | - |

### 4.1. Determination of Optimal Levels

**Table 4.** ANOVA outcomes

| Source | DF | Safety Factor | | | | | Equivalent Alternating Stress | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Seq SS | Adj MS | F | P | % Effect | Seq SS | Adj MS | F | P | % Effect |
| **A** | 2 | 1.101 | 0.551 | 9.31 | 0.03 | 6.29 | 3.65 | 1.83 | 12 | 0.02 | 0.22 |
| **B** | 2 | 16.158 | 8.079 | 136.6 | 0 | 92.35 | 1671.30 | 835.65 | 5492.63 | 0 | 99.75 |
| **Error** | 4 | 0.237 | 0.059 | | | 1.35 | 0.61 | 0.15 | | | 0.04 |
| **Total** | 8 | 17.495 | | | | 100 | 1675.56 | | | | 100 |
| | | R-Sq = 98.65% and R-Sq(adj) = 97.30% | | | | | R-Sq = 99.96% and R-Sq(adj) = 99.93% | | | | |

It was found that force and material type are significant determining parameters for responses since p values are less than 0.05 value. The best effective determining factors on safety factor were determined to be material type with 92.35% effect and force with 6.29 % effect, respectively. Error data was found as 1.35 for safety factor. In addition, the most meaningful determining parameters on equivalent alternating stress of beam were detected as material type with 99.75 % effect and force with 0.22 % effect, respectively. Error data for equivalent alternating stress was calculated as 0.04. To decide the determining factors consisting of optimal levels on safety factor and equivalent alternating stress of beams, the overall of each response characteristic (S/N ratios and numerical data) for all determining factors at each level were calculated. The response table was presented in Table 5.

**Table 5.** Response table for S/N ratios and means

| Level | Safety Factor | | | | Equivalent Alternating Stress | | | |
|---|---|---|---|---|---|---|---|---|
| | S/N data (dB) | | Means (-) | | S/N data (dB) | | Means (MPa) | |
| | A | B | A | B | A | B | A | B |
| **1** | 9.277 | 13.430 | 3.231 | 4.730 | -29.43 | -24.45 | 32.61 | 16.69 |
| **2** | 8.722 | 7.410 | 3.031 | 2.365 | -29.63 | -30.47 | 33.36 | 33.38 |
| **3** | 6.729 | 3.888 | 2.410 | 1.577 | -29.84 | -33.99 | 34.17 | 50.07 |
| **Delta** | 2.548 | 9.542 | 0.821 | 3.153 | 0.41 | 9.54 | 1.56 | 33.38 |
| **Rank** | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 |

From Table 5, the determining factors with the optimal levels for safety factor were selected as force and material type at the first levels. Also, the optimal levels of the determining factors for equivalent alternating stress were determined as the first levels of force and material type. Thus, designations for safety factor and equivalent alternating stress were calculated as $A_1B_1$ and $A_1B_1$, respectively.

### 4.2. Effects of Determining Factors

To evaluate the impact of force and material type on safety factor and equivalent alternating stress of beams, the numerical calculations were executed utilizing L9 orthogonal array. The average data of safety factor and equivalent alternating stress in accordance with all variable determining factor at level 1, 2, and 3 depending on finite element data and S/N ratio values were plotted in Figure 3a and Figure 3b, respectively.

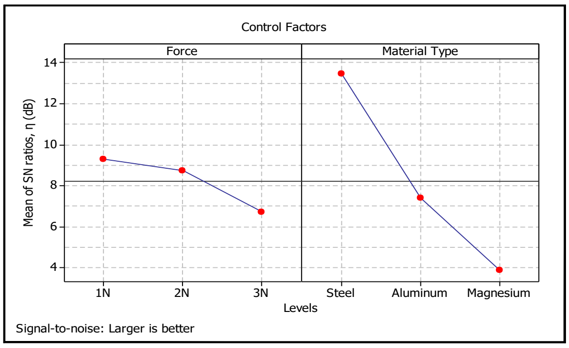


**Figure 3.** Influence of force and material type on safety factor

Figure 3 indications that safety factor decreases with the increase of levels of force values and material types. As can be understood from Figure 4, the increase of levels of force values and material types causes the increase of equivalent alternating stress.

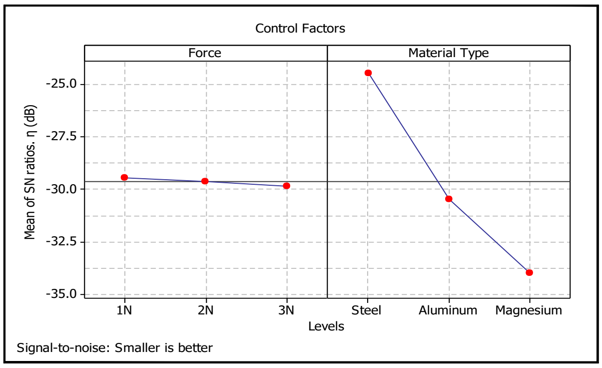


**Figure 4.** Influence of force and material type on equivalent alternating stress

These findings are due to the increase in the mechanical properties of the materials and the increase in the applied force value. The increase in the mechanical properties of the material can cause a decrease in the stress value. In this context, the mechanical properties of structural steel are higher than other materials. In addition, the increased force value can cause a decrease in the fatigue of the material. Increased fatigue can affect the safety factor of materials. Therefore, beams made of materials with high mechanical properties for high safety factor can be used under low force applications. This determination can be used in fatigue analysis.

### 4.3. Estimation of Optimum Responses

The optimum data of safety factor and equivalent alternating stress for the optimal levels of important variables which have already been chosen as force and material type at the first levels. The estimated numerical data of the responses may be considered using Equation 3 [26].

$$\mu_i = \overline{A_1} + \overline{B_1} - \overline{T_\iota} \qquad \textbf{(3)}$$

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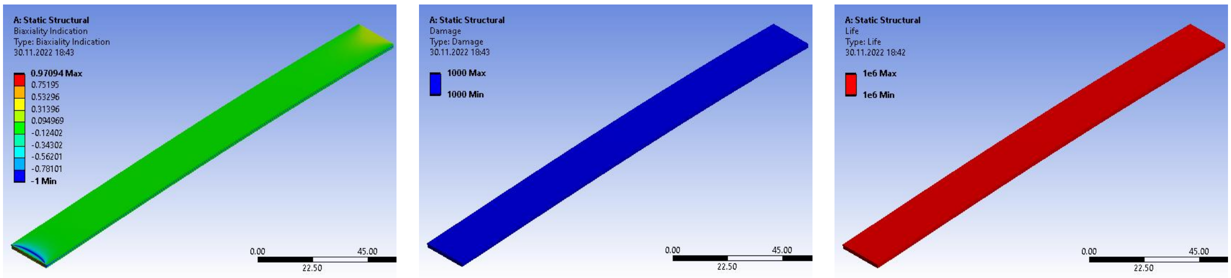
In Equation 3, the overall means of responses in agreement with Taguhi L9 orthogonal array were expressed as $\overline{T_{\iota}}$ and the overall means for safety factor and equivalent alternating stress were calculated as $\overline{T_{\mu}} = 2.8905$ and $\overline{T_{\sigma}} = 33.3798$, respectively. $\overline{A_1}$ and $\overline{B_1}$ show average data of responses at the first levels of force and material type. $\overline{A_1} = 3.231$ and $\overline{B_1} = 4.730$ was calculated for safety factor and $\overline{A_1} = 32.61$ and $\overline{B_1} = 16.69$ were determined for equivalent alternating stress. Substituting the data calculated for different terms, $\mu_{\mu} = 5.0705$ for safety factor and $\mu_{\sigma} = 15.9202$ MPa for equivalent alternating stress were obtained. Numerical and estimated results were demonstrated in Table 6.

Biaxiality indication, damage, and life for optimal designation were illustrated in Figure 4. From Figure 4, beam life and damage were calculated as $10^6$ cycles and 1000, respectively. Also, the most affected part of beam for biaxiality indication was monitored as clamped end of beam.

**Table 6.** Numerical and estimated results

| Test | Response | Numerical Result | Estimated Result | % Diff. |
|---|---|---|---|---|
| $A_1B_1$ | Safety Factor | 5.2871 | 5.0705 | 4.097 |
| | Stress (MPa) | 16.3040 | 15.9202 | 2.354 |




a) Biaxiality indication b) Damage c) Life

**Figure 4.** Fatigue result of beams with optimal levels: a) biaxiality indication , b) damage, and c) life

## 5. Conclusions

In this study, effect of force and material type on safety factor and equivalent alternating stress of beams with clamped-free boundary conditions was investigated utilizing numerical and Taguchi approaches. ANSYS Workbench software was implemented as numerical approach. Numerical solutions were achieved utilizing Taguchi L9 orthogonal array consisting of two determining factors, which have three levels. Force and material type were assumed as determining factors. Determining factors with optimum levels and their effects were selected utilizing analysis of signal-to-noise ratio. In addition, % effect and significant level of each determining factor on safety factor and equivalent alternating stress were obtained by ANOVA.

The conclusions of the mathematical paper may be presented as follows:

- Increase of forces applied at the free end of beams causes a decreasing in safety factor and an increase in equivalent alternating stress.
- The optimum material for safety factor and equivalent alternating stress was chosen as structure steel compared to aluminum and magnesium materials.
- The most meaningful determining parameters on safety factor were found as material type with 92.35% impact and force with 6.29 % impact, respectively.
- The most efficient determining parameters on equivalent alternating stress were noticed as material type with 99.75 % impact and force with 0.22 % impact, respectively.
- Differences between numerical and estimated results obtained using determining factors with optimum levels were calculated as 4.097 % for safety factor and 2.354 % for equivalent alternating stress.

## Author's Contributions

**Savaş Evran:** Created and composed the manuscript, conducted the result analysis.

## Ethics

There are no ethical issues after the publication of this manuscript.

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