Science Arena Publications
Specialty Journal of Engineering and Applied Science
ISSN: 2520-5943
Available online at www.sciarena.com
2018, Vol, 3 (4):14-26

Simulation and Material Selection for Railway Sleeper Based on Absorbing Energy

Alireza Khavari[1], Nathan Jafarian Jam[2]*

[1]Department of Mechanical Engineering, Pardis branch, Islamic Azad University, Pardis, Iran.
[2]Assistant professor, Department of Mechanical Engineering, Pardis branch, Islamic Azad University, Pardis, Iran.

***Corresponding Author**
Email: jafarian@pardisiau.ac.ir

Abstract: *Wood is one of the earliest materials that has been used for making railway sleepers. The sensitivity of wood to atmosphere and fire and consequently their early destruction lead to the application of novel materials such as concrete to cover the deficiencies of wood. Although concrete solely does not have high tensile strength and after a while, with the existence of microcracks, it would be destroyed. In addition, Thus, wherever rapid vibration damping is required, additives should be applied or the sleepers' material must be changed. In this study, by application of fuzzy algorithm and membership functions, the most suitable material for construction of sleepers based on absorbing energy is investigated. The aforementioned approach requires preparing a list of candidate materials. For instance, if the selected material is reinforced concrete with basalt fibers, the best proportion of concrete and fibers should be calculated. The applied equations are Euler equations for two fixed-end beam and American standard is used for changing load. Moreover, in order to represent the selected material and detailed examination, appropriate finite element software is applied. The final choices for the materials of sleepers are reached by the combination of the software results. In addition, the study of the displacement and stress in reinforced sleeper based on the selected material is done and due to negligible displacement and positioning of the stress in compressive direction, the weak point of concrete in tensile load capacity is covered and the capacity of vibrating load in the proposed model is enhanced.*

Keywords: *Sleeper, Railway, Reinforced Concrete, Basalt Fibers, Fuzzy Algorithm, Material Selection*

INTRODUCTION

Nowadays, the importance of the material role in engineering design is properly understood. Generally, after the conceptual design stage, designers always search for materials with special characteristics that can improve the performance of the optimized system by satisfying all the constraints. In the final stage of design, the concentration is usually on the comparison of the limited set of features of materials and selecting one of them which has the most compatibility with requirements in entire set that is called "material selection". According to the available data, the existence of more than 40000 metal alloys and the same numbers of nonmetal engineered materials such as plastics, ceramics, glasses, composite materials and semiconductive is estimated. This large number of materials and numerously available engineering method of manufacturing, in addition to providing sophisticated relations among different selected parameters, usually causes difficulty and time-consuming decision making in selecting materials among all the available choices. Based on the experiences, decision approaches along with engineering, are combined in the process of manufacturing the pieces. In the engineering section, materials and production processes are considered in the design and in the decision-making section, the main focus is on material selection.

Although material selection is usually done for producing a new piece, it is applied in many areas like material substitution. Unlike in scientific facts that there is a unique solution for a problem, in material selection and substitution decisions, considering advantages, constraints and occasions is necessary which may lead to different satisfying results. This phenomenon is in line with the reality as distinct pieces are produced for different constructions and usually with different materials and even processes.

By considering the importance of materials in design and broad variety of them, material selection is considered as a determining factor. In this regard, there are various material selection methods that each of them has its own pros and cons. Thus, in this study, one of the most suitable methods of material selection is introduced briefly and it used in the material selection of railway sleepers. An important aspect of this research is that material selection is applied in a way to choose novel materials. As finding the characteristics of materials is time-consuming and costly, materials with available specifications may be used in this study. However, the method of this study can be integrated with finding the features of new materials and adding them to the list of candidate materials or upgrading the existing material characteristics with more detailed data to reach more desirable results.

Sleepers can be used as bearing for the rails and as a factor to transfer and distribution of load on the roadbed. Identifying sleeper and technical and general specification of its different types, alongside knowledge of design and analyzing has a significant importance.

Several studies that have been carried out in this regard are as follows:

Ashby et al. (2003) reviewed strategies or methods of material selection. According to this study, material selection is classified into three categories. A) free search which is based on quantitative analysis and the most well-known type of it, is graphical or ranking methods (Ashby, 1992). B) checklist/questionnaire method which is based on experiences like reports that are based on knowledge or intelligent data that has an interrogative structure and ultimately this structure results in a solution for optimal design. C) inductive reasoning approach and analog procedure (Trethewey et al., 1998).

Garton et al. (1992) applied charts of fatigue characteristics for the design of minimum weight based on infinite life. Another approach in material selection is weighted properties method (WPM). This method rates candidate materials based on performance indices that are reached by mathematical calculation (Farag, 1997). In cases where a large number of material specifications are involved in the problem and the importance of each property is not significant, determining the weighted factor of α is complicated. Consequently, the reliability of the method is diminished. So digital logic (DL) method for determining α values is proposed (Farag, 1997).

Material and Methods

- **Modeling sleepers**

In order to convert static load to semi-static load, the static load should be multiplied by a number known as impact coefficient, to consider the effects of impact on a sleeper that increases the applied force. Impact coefficient can be calculated from equation (1) (Arema manual for railway engineering, 2006):

$$\emptyset = 1 + 5.21\frac{V}{\mathrm{D}} \qquad (1)$$

Where V is the train speed in km/h, D is the diameter of wheel in mm and ø is dynamic load coefficient. In addition, in order to determine the load of rail on the sleeper, the method of load distribution on three sleepers is used. In this way, the maximum load on sleepers occurs when the load of the wheel on rail is distributed among three adjacent sleepers. In this method, if the load of rail seat on the middle sleeper is x percent and the load of rail on two adjacent sleepers is x/2 percent, usually, 50% of x is assumed as wheel design load (equal to 25% of axial design). So, the maximum load of the rail seat is as following:

$$q_r = 0.5p \tag{2}$$

Where p (kN) is the load of wheel design.

- **Material selection methods**

Three main methods of material selection are:

- Ashby method
- Z transformation method
- Fuzzy method

In all the mechanical designs, the most basic step is searching for suitable and conventional materials. As an illustration, wood is never considered for the design of cylinder of automobiles Recently, various composite and concrete materials have been introduced for material selection of sleeper. Thus, due to the fact that almost all the railroad industries use concrete or composite materials, in this research, these type of materials has been selected as candidates. In addition to the proposed conventional materials, basalt fibers are included in the list of candidate materials. By considering the considerable advances in the production of basalt fibers and their low cost, they can be introduced as one of the most suitable materials in manufacturing sleepers with high longevity.

- **Mechanical Investigation**

In this study, material selection and optimization of a sleeperare investigated. The real dimension of the model is represented in Figure 1.

Figure 1. The pre-stressed sleeper B_{70}

The dimension of a sleeper is shown in Figure 2. SolidWorks software is used to perform the basic simplifications. These simplifications include the elimination of fillets for increasing reliability in a way that by performing simplification, the results should be higher than the normal condition which enables the application of higher reliability coefficients. In that way, material selection can be done according to the geometry.

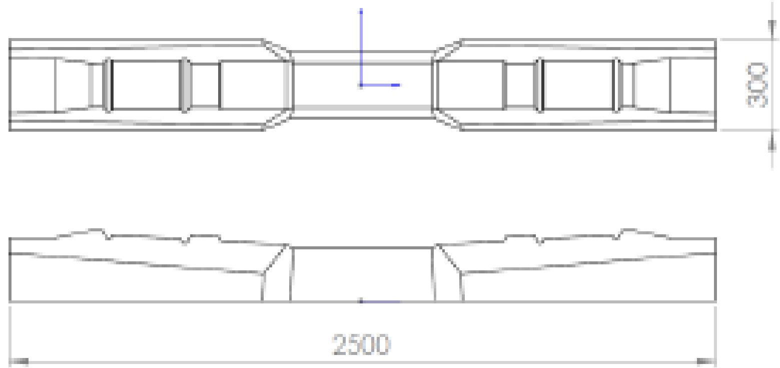

Figure 2. The dimensions of the pre-stressed sleeper B_{70}

The first step in fuzzy material selection is a comparison of the model with an ideal material. In this study, concrete is selected as the ideal material and this material is applied only for satisfying constraints of fuzzy functions. Also since concrete has great similarity with the candidate materials, the comparison between them can provide good results. Despite several deficiencies of concrete, high rate of production and affordable cost cause its widespread application. So, according to the geometry and specification of material, ABAQUS finite element software is used for analysis.

- **The Model and Discretization**

Modeling is first carried out in solid works software, then transfered to ABAQUS software and elements were determined. In this study,three-dimensional element C3D8R is used for determining elements. In some points, where the stress concentration is higher, smaller elements are used.

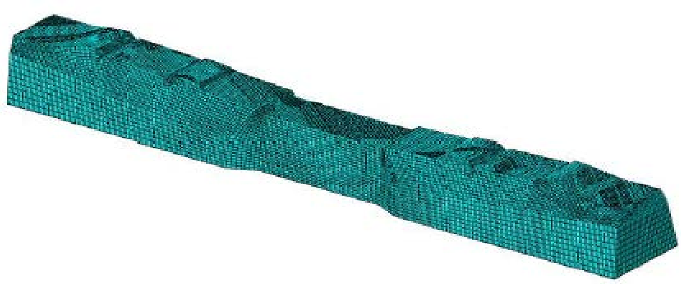

Figure 3. The elements of the pre-stressed sleeper B_{70}

Analysis of vibration

In an analysis of vibrations, natural modes of the system are assessed. It should be considered that the frequency of these modes should not be smaller than the frequency of the movement of the wheels. This condition imposes intense loads of fatigue on sleeper and sleeper would be destroyed in the shortest possible time. 10 frequencies are investigated in Table 1. The most important frequency is the first frequency which causes fatigue in bearing.

Table 1. 10 first frequency of the pre-stressedsleeper B_{70} model

Mode	1	2	3	4	5	6	7	8	9	10
Frequency (r/sec)	194	303	330	448	640	687	805	949	1109	1237

Therefore, according to the frequency, the minimum and maximum value of the Young module can be investigated.

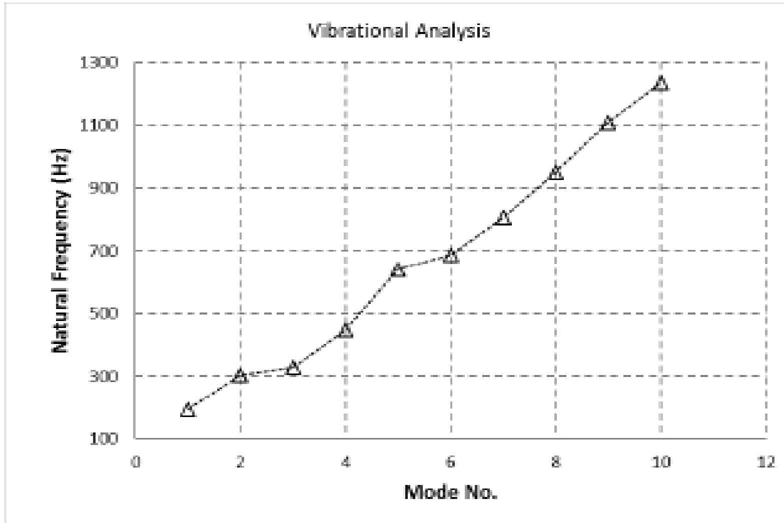

Figure 4. The graph of 10 first frequency of the pre-stressedsleeper B_{70} model

Semi-static analysis

Figure 5 shows the loading of rail on the sleeper and boundary condition.

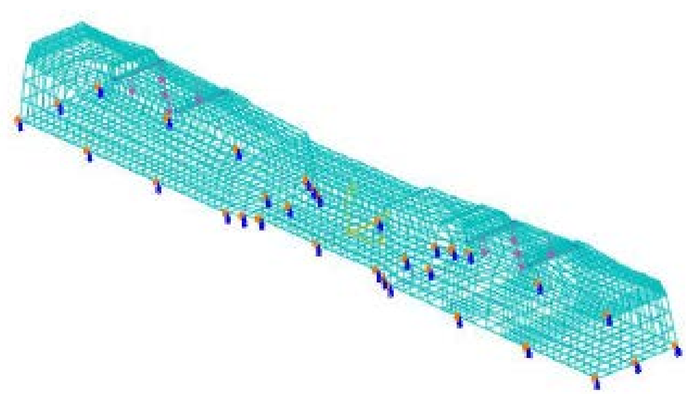

Figure 5. The force from the wheel on the critical sleeper

Figure 6 shows the distribution of the stress caused by the force of the wheel on a critical sleeper. Accordingly, the stress on the contact surface of rail and wheel has the highest value.

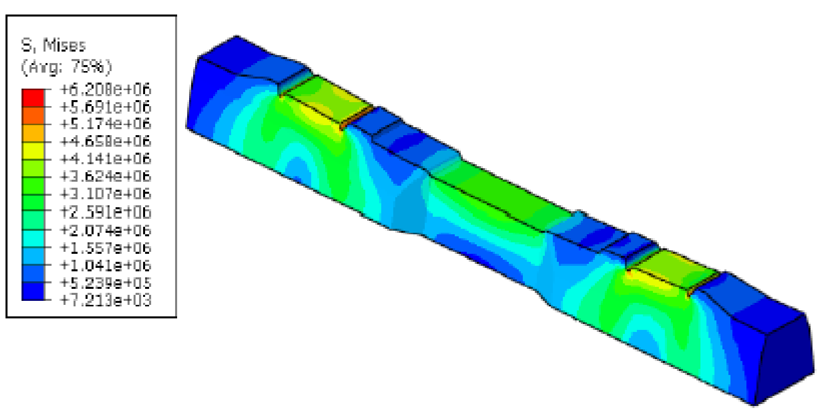

Figure 6. distribution of the stress on the critical sleeper to find the constraints of fuzzy functions

- **Fuzzy logic in material selection**

Fuzzy logic in material selection has been investigated for the first time by Sarfaraz et al. (SarfarazKhabbaz et al., 2008). This method not only has more compatibility with the design criteria rather than previous methods but also covers the deficiencies of the former approaches. In this section, fuzzy logic is partially investigated and then in order to make simpler use of this method, MATLAB software is used which provide a fuzzy environment for decision-making problem alongside complex coding for an easier way of determining rules.

Candidate materials for material selection based on the fuzzy method

In this section according to the calculations which have done on the concrete sleeper, fuzzy functions for determining components are identified. At first, by summarizing the candidate materials in Table 2, the process of material selection becomes more precise.

Table 2. The list of Candidate materials for material selection based on the fuzzy method

	Pressure strength per density and cost	**stress strength per density and cost**	**Yang module per density and cost**	**Impact Resistance**	**Moisture resistance**
	UTSp/D	UTS/D	YM/D	Impact Resistance (1-5)	MECo
	max	max	max	max	Min
Steel	4.62E+04	4.62E+04	2.69E+07	7	3
Balsa (wood)	5.63E+04	4.56E+05	1.98E+04	2.2	2
Concrete	2.54E+04	1.23E+03	1.80E+07	0.9	4
GFRC (1)-0.25% Glass Fiber	2.60E+04	1.44E+03	1.69E+07	1	4
GFRC (2)-0.50% Glass Fiber	2.60E+04	1.49E+03	1.69E+07	1.3	4
GFRC (3)-0.75% Glass Fiber	2.77E+04	1.49E+03	1.70E+07	1.4	4
GFRC (4)-1.00% Glass Fiber	2.70E+04	1.45E+03	1.78E+07	1.5	4
BFRC (1)-0.25% Basalt Fiber	2.60E+04	1.36E+03	1.82E+07	1	5
BFRC (2)-0.50% Basalt Fiber	2.76E+04	1.36E+03	1.86E+07	1.2	5
BFRC (3)-075% Basalt Fiber	2.72E+04	1.48E+03	1.77E+07	1.25	5
BFRC (4)-1.00% Basalt Fiber	2.71E+04	1.73E+03	1.77E+07	1.4	5

Determining fuzzy functions

The natural frequency of the first sleeper should not be smaller than 1500 radians per minute (25 radians per second or Hertz) to prevent fatigue that caused by resonance of frequency of train wheels. Therefore, since the analysis of the vibrations is not smaller than this value and natural frequency has a direct relation with yang module and an inverse relation with density, E/p (yang module on density) of plain concrete is calculated and is chosen as criteria.

$$\left(\frac{E}{P}\right) = \frac{16.9}{2.444} \cong 7 \tag{3}$$

So, it can be concluded that the value of 7 for the beginning of the excellent fuzzy functions' graph is appropriate. Figure 7 shows the graph of yang module membership against density.

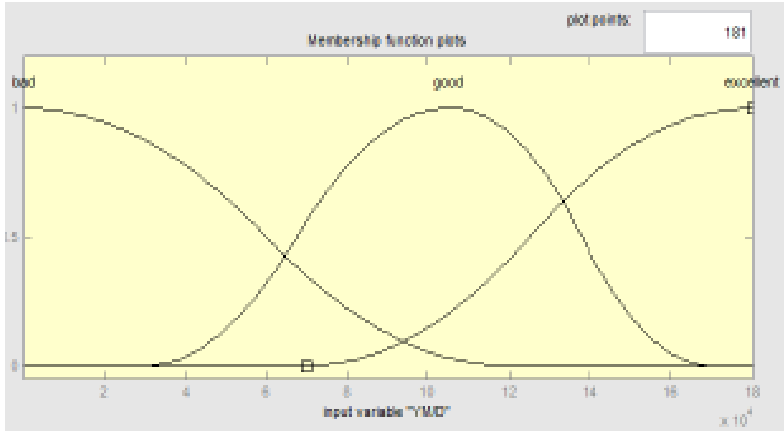

Figure 7. Fuzzy function for yang module against the weight

In addition, Figure 8 represents the fuzzy functions of material performance. In order to reach more precise results, performance is classified into five functions including "excellent", "good", "average", "bad" and "terrible".

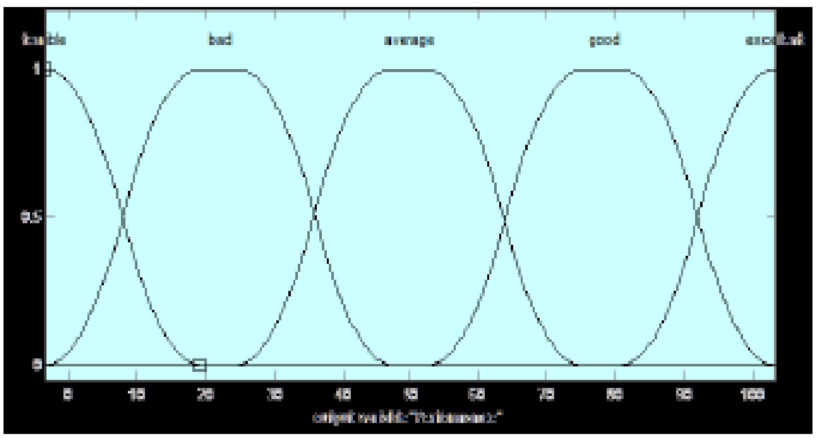

Figure 8. Fuzzy functions for performance coefficient of materials

If-then rules

In this section, if-then rules should be used to make decision and apply the logical part of fuzzy logic. If-then rules are represented in Table 3 and based on the set rules, the importance of pressure tolerance is expressed.

Table 3. If-then rules for decision making based on the fuzzy method

	Pressure strength per density		Tensile strength per density		Yang module per density		Impact Resistance		Moisture resistance per density		Material Performance
	UTSp/D		UTS/D		YM/D				MECo/D		
	max		max		max		min		min		
if	3	and	0	and	3	and	3	and	3	then	5
if	1	and	0	and	0	and	0	and	0	then	1
if	3	and	0	and	2	and	3	and	3	then	4
if	3	and	0	and	0	and	0	and	3	then	4
if	3	and	0	and	1	and	1	and	1	then	3
if	2	and	0	and	2	and	2	and	2	then	3
if	2	and	0	and	3	and	3	and	3	then	4
if	2	and	0	and	2	and	1	and	1	then	2

if	2	and	0	and	1	and	3	and	3	then	3
if	1	and	0	and	3	and	3	and	3	then	1
	0=Not Status		0=Not Status		0=Not Status		0=Not Status		0=Not Status		1=Terrible

Results of decision-making

Figure 4 is the results of decision functions. According to this table, steel was chosen as a first material which due to its high flexural and tensile strength and also significant resistance toward fatigue is a proper material for a sleeper. However, high price and the significant cost of manufacturingput a heavy financial burden on manufacturers and consumers. So, reinforced concrete with fibers can be a suitable choice for manufacturing different types of sleepers by considering its high resistance and lower cost of manufacturing in large quantities.

Table 4. The results of material selection through candidate materials

'materials'	'Fuzzy Logic'	'Z-transformation'
'Steel'	81.36	1.6391
BFRC-4'	78.129	0.0148
GFRC-4'	78.024	-0.0357
GFRC-3 '	78.02	0.0974
'GFRC-2'	77.98	-0.1231
'BFRC-3'	77.973	0.034
'GFRC-1'	77.972	-0.2511
'Concrete'	77.972	-0.275
'BFRC-1'	77.971	-0.0868
'BFRC-2'	77.971	0.0502
'wood-Balsa '	49.701	-0.242
'GFRP'	37.279	-0.8218

Analysis of data

The analysis of results can be carried out after material selection and determining the percentage of fibers in sleepers and then validation of the optimized material is possible. in this study, two methods of manufacturing of sleeper are used that are plain and pre-stressed sleepers. However, usually for higher pressure resistance of sleepers and lower exposure of the material to both tensile and pressure stress, pre-stressed sleepers are applied.

- **static analysis**

Modeling of pre-stressed sleepers is represented in Figure 9. The red lines are related to bars with 5 mm diameter which is designed to tolerate tensile in a way that the lowest tensile stress is put on reinforced concrete with fibers. The aforementioned modeling is compared with the model without the bar.

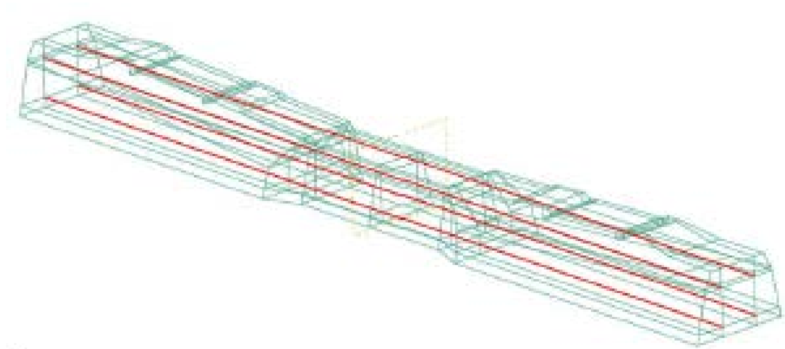

Figure 9. Modeling the pre-stressed sleeper

In this work, two-dimensional elements C3D8R and beam element are used for meshing.

Figure 10. Meshing of a sleeper based on two-dimensional elements C3D8R and beam element B31

The amount of stress inside bars is set to 5 megaPascal that can expose most of the sleepers to pressure stress for efficient application of reinforced concrete toward dynamic and weight loads. Figure 11 represents the way of loading on a sleeper. In this section, in order to better simulation of the bed and more precise calculation, an elastic volume which is equivalent of the modulus of resistance of bed is applied.

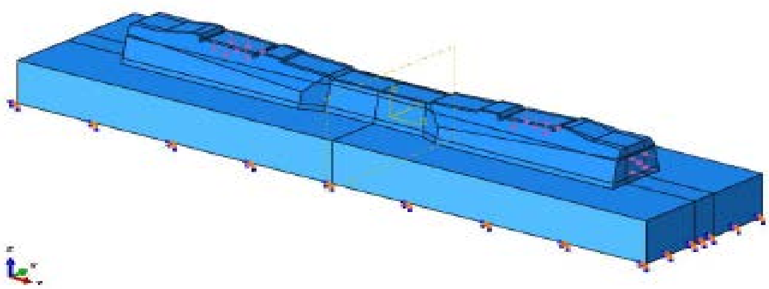

Figure 11. Loading and boundary condition on the sleeper model to the static and dynamic analysis

The analysis is carried out on both models after loading and meshing. Figure 12 and 13 show the distribution of the stress of Von Mises static analysis on the pre-stressed sleeper and the distribution of the stress of Von Mises static analysis on the plain sleeper, respectively. In addition, figure 14 shows the designed path on the sleeper for investigating the distribution of stress and displacement.

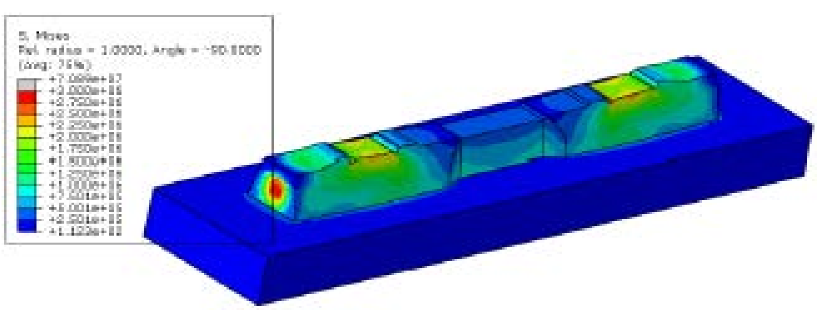

Figure 12. Distribution of the stress of Von Mises static analysis on the pre-stressed sleeper

According toF 12, the maximum stress is in the contact point of rails and also in the beginning and end of sleepers which is due to high pressure of bars. However, since the amount of this stress is low, the area of contours is lessened for repressing the distribution.

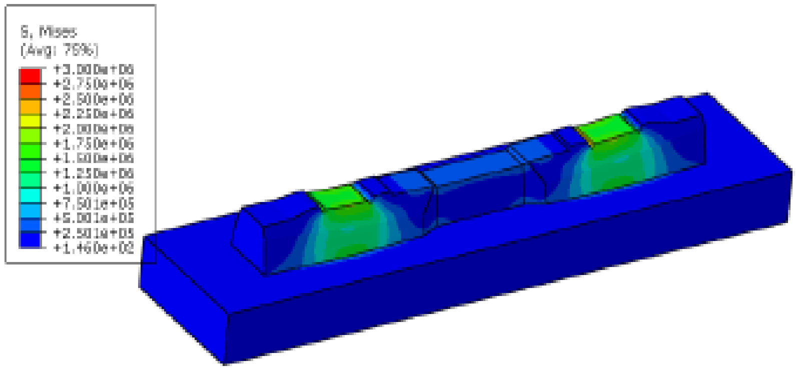

Figure 13. Distribution of the stress of Von Mises static analysis on the sleeper without bar

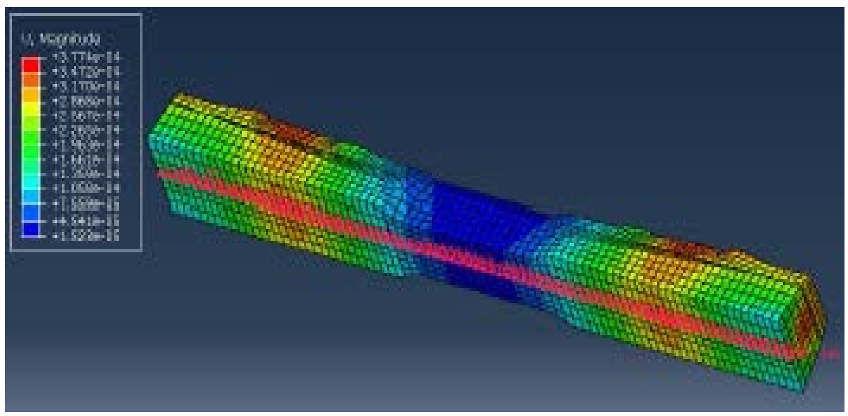

Figure 14. The designed path on the sleeper for investigating the distribution of stress and displacement.

Figure 15 represents the displacement for both models. According to this figure, displacement is almost equal in two models and passes the same distance. The maximum displacement is equal to 0.3 millimeter which is a negligible amount and it is anticipated that by considering this small displacement, vibration load would be tolerated.

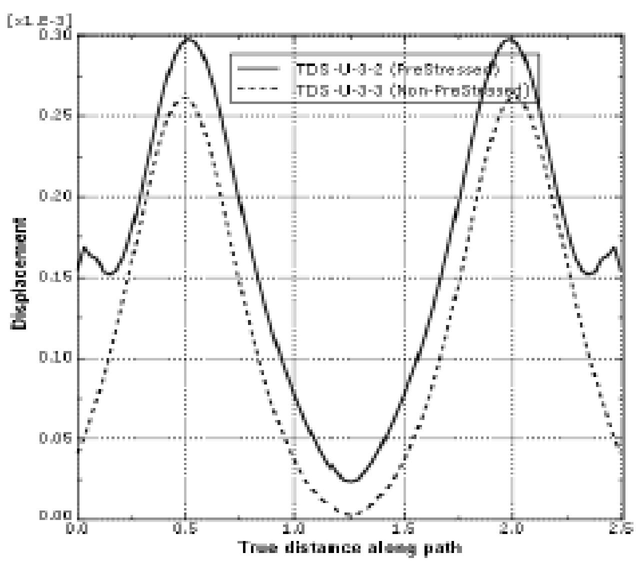

Figure 15. Displacement in the selected path through the length of sleeper

- **Dynamic analysis**

In this section, for dynamic analysis of each cycle of force on the next cycle, Dynamic-Implicit analysis is applied. For better understanding, this approach, assume a sineload on a period is exerted on the sleeper and causes the sleeper to oscillate. During this oscillation, another cyclic load is applied to a sleeper. In this condition, the impact of second cyclic force is investigated on the previous load. The value of load is considered to be the same amount for both sections which is $\boldsymbol{Pdwheel = 203.15KN}$. Figure 16 represents the amount of load on sleeper in cyclic form. The a a speed of train is considered to be kilometers per hour.

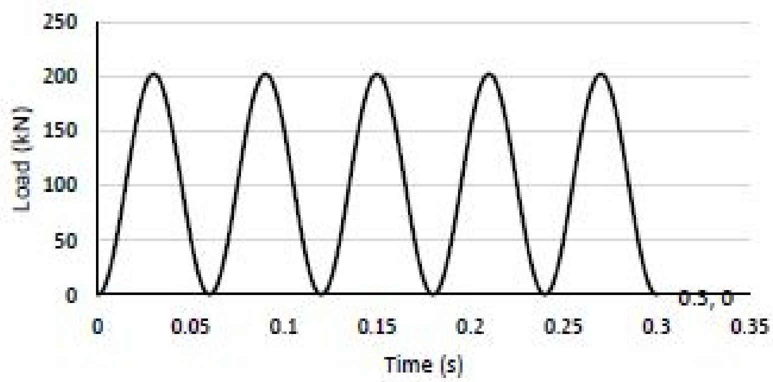

Figure 16. The amount of periodic load on the sleeper from the movement of a train with 60 km/h speed

Therefore, the effects of forces on the range of displacement and stress can be analyzed by knowing the cyclic force and then validate material selection after static analysis. Critical points should be considered for investigation. The maximum displacement and stress is at the contact area of rail to sleeper which is depicted in Figure 17.

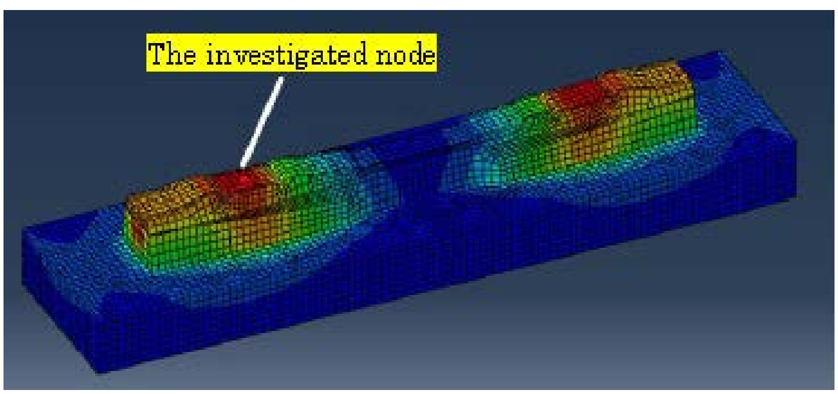

Figure 17. The investigated node that is located on the contact point of rail and sleeper

The graph which is represented in Figure 18 indicates the displacement in the critical point of Figure 17. According to Figure 18, as the train path, reinforced sleeper adjusts its frequency with the oscillating of the load and by the end of the loading, considerably reduces its oscillation to minimize fatigue.

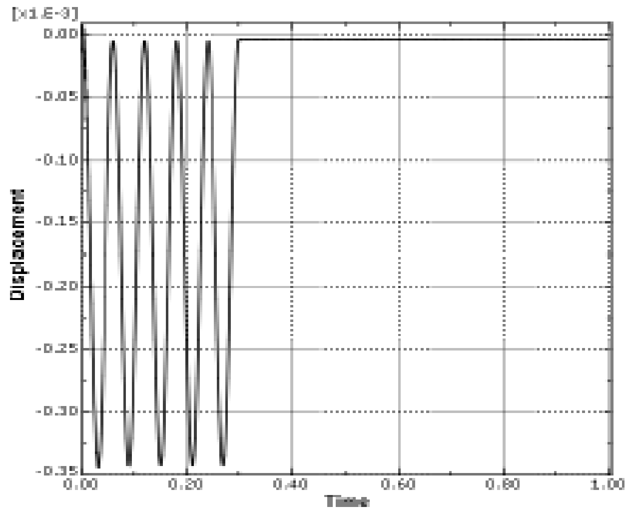

Figure 18. Sleeper displacement based on the movement of train on it in the critical node

Conclusion

In this study, material selection is carried out based on the design and fuzzy logic. The results of this research show that the application of reinforced concrete can in one hand provide the required strength and on the other hand be more economical in comparison to steel. Choosing concrete as a base material for better performance and higher life of sleepers makes it possible to use conventional additives such as propylene fibers, glasses and basalt. The result of this study shows that basalt has better performance among other additives and the validation of this result is done in this research. According to the performance of basalt and method of decision-making, the following results can be reached:

1. In the conventional fuzzy method, in order to make a decision, determining membership functions are done by the user and there is no limitation in this regard. Thus, a more efficient decision can be made by application of these functions.
2. In the fuzzy method, thorugh determining the importance degree of each parameter in if-then rules, the more important as well as determinant parameters can be considered in decision-making. For instance, the issue of compressive stress is of high importance which increases the rank of the concrete with basalt fibers. But, in case tensile stress is considered, wood can have a better performance.
3. After decision-making, for better performance and putting concrete under pressure stress area that causes better performance, in the selection of reinforced concrete with basalt fibers, bars for prestressing of concrete can be applied. These bars can be used during the manufacturing process in a way that they are placed in the shutteringand exposing them to stress. The amount of tensile should be analyzed in the way that sleeper be under the area of pressure stress during loading.
4. The number of candidate materials can be added in order to increase or decrease the proportion of basalt to concrete and restart the process of decision-making.
5. Although steel stands on top of concrete in material selection, due to its complex synthesis and expensive materials, is not selected and concrete was chosen as the best material after steel. Choosing concrete necessitates the process of prestressing to reach results that satisfy the distance of the place of rail bearings. So, displacement as a result of prestressing is important.

Suggestions and future works

1. Determination of the equivalent values of the membership functions can be done by other methods and their results can be compared with the proposed method in this study.

2. For investigation of the proposed method, different membership functions that have different shapes can be used and the final results can be compared with each other.
3. According to the proposed procedure for material selection of the sleeper, by accessing to HCF properties of concrete which requires expensive tests, redo the process of material selection and compare the achieved results with the results of this study.
4. As the specification of reinforced concrete with basalt fibers is not accessible as a result of limited experiments in this regard, creating a data bank for the specification of materials in the university can be a solution for this problem.
5. The accuracy of the result of this study can be more investigated by manufacturing a sample sleeper from the selected material.

Reference

1. Arema manual for railway engineering 2006.
2. Ashby MF, Brechet YJM, Cebon D, Salvo L. Selection strategies for materials and processes. Mater Design 2003; 25: 51–67.
3. Ashby MF. Material selection in mechanical design. Oxford: Pergamon Press; 1992.
4. Farag M. Materials selection for engineering design. London: Prentice Hall Europe; 1997.
5. Farag M. Materials selection for engineering design. Prentice Hall; 1997. p. 227–234.
6. Garton DA, Kang KJ, Fleck NA, Ashby MF. Materials selection for minimum weight fatigue design. Theor Concept Numer Anal Fatigue 1992:359–76.
7. SarfarazKhabbaz R, DehghanManshadi B, Abedian A, Mahmudi R. A simplified fuzzy logic approach for materials selection in mechanical engineering design. Mater Des 2008.
8. Trethewey KR, Wood RJK, Puget Y, Roberge PR. Development of a knowledge-based system for materials management. Mater Des 1998; 19:39–56.