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Durability Analyses of a Rubber to Metal Anti-vibration Cone Mount, Subjected to a Random Type Load Signal by using Damage Models in Finite Element Method

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Present study proposes a method for lifetime prediction of rubber-to-metal anti-vibration mounts, which can be divided into two approaches. Method is especially suitable for random type load signal, which is used for rubber mount validation tests. Method employs the cyclic tests until specimen failure and the Wöhler diagrams. Random type load signal is used for strain based level crossing operation and after that, life time prediction can be done by using the inputs from Wöhler diagrams and level crossing operations. Numerical approach and FEA approach only differ from each other in the determination of unit damages in making the life-time predictions.

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1. Introduction

Rubber to metal anti-vibration cone mounts are used in a wide range of industrial applications, which have different loading characteristics. These kinds of cone mounts are produced mostly with standard dimensions and typical rubber compounds. A design engineer can create more efficient designs using the detailed information about the sub-components. Static and dynamic responses are the basic mechanical properties of an anti-vibration product. In system development activities, effective usage of cone mounts can be improved, when their long term behavior, like durability, is technically defined, together with their static and dynamic characteristics.

Durability is a key parameter in the design of a long-life and stable system. On the other side, warranty regulations and the end user expectation are increasing day by day. Several fatigue life prediction studies exist [1–3] in academical and industrial research areas, which depend on different approaches like cyclic fatigue, road load data and ext. road load data. Such data is collected during a field application, as a way to validate the product, if a physical specimen exists.

Chang S. Woo et al. proposed a method, which basically represents a fatigue life prediction for automotive applications without using a physical sample [4]. Present study presents a method of durability determination [5] of a cone mount. Method includes two approaches to define durability performance, which are the numerical calculation and the finite element method (FEM).

A commercial FEA code MSC Marc is used for finite element analysis in the study. Durability behavior of cone mount is verified on a hydraulic dynamic test bench, which is able to run random road load data. Loading profile is specially defined as random type load signal (RTLS), to create a wide usage platform for proposed method in system development activities.

Damage model parameters, which are calculated as a result of data acquisition activities on standard tensile and compression rubber test specimens, are used to setup and verify the FEA models. The strain-based level crossing is applied to RTLS and damage models are set, according to repetition and strain level of the signal. Verification performance and effectiveness of the proposed method is reported in a comparison between FEA results and physical test results for durability behavior of the same cone mount.

2. Experiments and methods

2.1. Rubber material

Elastomer materials are neglected in this study. Vulcanized natural rubber with carbon black filler is used, which has the middle range hardness of international rubber hardness degree 55ShA. Compound recipe is summarized in Table I.

TABLE I

Recipe for natural rubber compound.

Ingredient	55ShA Natural rubber [phr]
elastomer	100
carbon black	57
plasticizers	6
curing agent	3
other	17

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2.2. Specimen level tests

The behavior of rubber material is defined using constitutive material models in FEM, where hyperelastic, viscoelastic, damping, creep, damage and some other responses can be calculated. To simulate all these responses, the important material properties must be defined by material coefficients in the constitutive material models. At the basic level, strain tensors represent material behavior in strain energy functions and differences of the constitutive models come in account when incompressibility and degree of function are considered. In all cases, the coefficients of material models have to be calculated to be used in the FEA.

The focus of present study is to determine the damage model coefficients, using physical tests of standard test specimens. Shear is the dominant loading type for a cone mount in the present study. Therefore, a four-arm shear specimens are used, as shown in Fig. 1a [6].

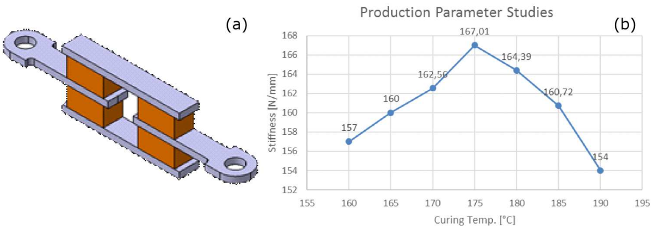

Fig. 1. (a) Four-arms shear specimen. (b) Production trails for optimum parameter determination (sample graph).

Specimens were produced in injection type vulcanization presses by using natural rubber compound, the recipe of which is given in Table I. Production parameters were defined as a result of production trails at different temperatures and for different curing times. Stiffness and the peek point of stiffness vs temperature curve were used as indicators of production trails. For all tests the Mullins effect was considered to have more robust results [9].

In Fig. 1b, the selected parameters belong to point 3 from left side. It is not preferable to select the maximum point or any points on the decreasing side of a curve, to prevent the reversion of vulcanized rubber.

In a typical RLD durability program, test parameters are defined as a repetition of RTLS. For instance, a 323 s long RTLS is used in the present study. Figure 2a shows a sample signal, which can include force or displacement values versus time. In both cases durability response behavior is represented as a result of strain repetition on the product, during whole RLD program.

On specimen study level, the strain repetition is defined as sinusoidal cyclic signal. Durability performances of four-arm shear specimens were evaluated by using test parameters in Table II. Specimens were tested until failure. Frequencies were defined considering strain rate status. Strain rates are equal for each strain level [7].

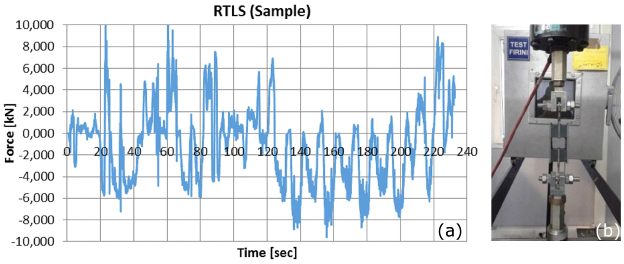

Fig. 2. (a) Random type load signal (sample graph), (b) specimen level test setup.

TABLE II

Test parameters of specimen level durability test.

Parameter sets		Compression specimen	Four-arm shear specimen
Set 1	Strain level (S) [%]	S-10	S-25
	Frequency (F)		F-24
Set 2	Strain level (S) [%]	S-30	S-50
	Frequency (F)		F-12
Set 3	Strain level (S) [%]	S-70	S-100
	Frequency (F)		F-3

Specimens were cooled during entire test to prevent heat buildup in rubber body [8]. Temperature was controlled every 2 hours and was kept under 40 °C, surface temperature. Measurements were taken with a laser thermometer. Our test setup is shown in Fig. 2b.

2.3. Damage calculation – numerical approach

In industrial usage, fail criterion is defined as ±20% change in static stiffness of rubber element according to initial measurement. In present study the same criterion was used. Specimens were tested until they failed and at each 20 000 cycles, static stiffness measurements were repeated. Wöhler curves were created by using the measurement points.

To identify the amount of damage per cycle, unit damage (UD) parameter was used. UD was calculated per strain level with the help of Wöhler curve. UD is expressed in Eq. (1), where 100% is total static stiffness change of the product and N is number of cycles. This simple equation gives the damage, which is caused by one cycle at the specified strain level. UD values create the input for the product level test study.

$$\mathrm{UD} = \frac{100\%}{N}. \tag{1}$$

The proposed calculation method with numerical approach depends on UD and strain level distribution in RTLS. Strain level distribution was determined by using a level crossing graph. Vertical axis of the level crossing graph was created by using min and max strain values in RTLS. RTLS is a displacement dependent signal and strain levels were calculated by using displacement values in signal and cone mount geometry. Distance between min and max strain levels is divided into 20 equal intervals to create the level crossing template. Horizontal axis shows the repetition number of strain level in whole signal.

The total damage (TD) of a rubber mount can be calculated as a combination of different strain levels and different UDs. Equation (2) shows the TD, where UD_i is the unit damage of strain level, which comes from specimen level tests, rep_i is the repetition of strain level in RTLS, TP is total number of point in RTLS, S is severity of strain level and SR is signal repetition during RLD program. Evaluation criterion was defined as TD $< 20\%$ of static stiffness change for RLD program. Our approach aims to identify the SR values of program.

$$\mathrm{TD} = \sum_{i=1}^{20} \left(|\mathrm{UD}_i| \times \frac{\mathrm{rep}_i}{\mathrm{TP}} \right) \times S \times \mathrm{SR}. \tag{2}$$

2.4. Damage calculation – FEA approach

FEA approach only differs from the numerical approach in the UD determination method. UD is calculated as a result of long cyclic durability tests in numerical approach. On the other hand, UD is calculated as a result of FEA calculation by using hyperelastic and damage constitutive models, which is specialized for rubber materials. Determination of hyperelastic material model coefficient is out of the scope of the present study. Damage model coefficients were determined by using experimental data fitting tools in MSC Marc [10].

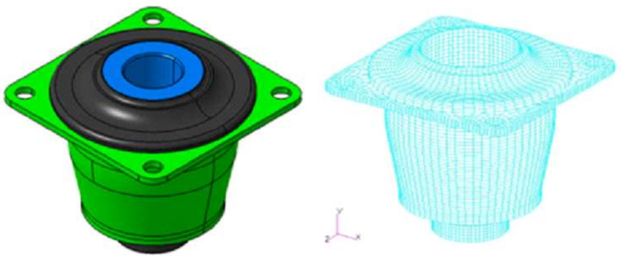

Fig. 3. Cone mount CAD and FEA models.

Cone mount was meshed and analyzed to determine the UD. Figure 3 shows the FEA model of the cone mount. After determining the UD values for different strain levels, rest of the fatigue life prediction is the same as in the numerical approach. Equation (3) expresses the UD calculation from FEA. $\mathrm{Force}_{\max\ i}$ represents the initial reaction force against applied displacement. Applied displacement gives the applied strain level related with the specimen geometry.

$$\mathrm{UD}_{\mathrm{FEA}} = \frac{\mathrm{Force}_{\max\ i} - \mathrm{Force}_{\max\ i+1}}{\text{Applied Displacement}}. \tag{3}$$

2.5. Product level tests

After specimen level tests, cone mount was tested with a RLD program. One axis hydraulic test bench was used for product level tests, as shown in Fig. 4. Same method was used for product level tests. During RLD program the static stiffness was monitored to determine the fail status of the product.

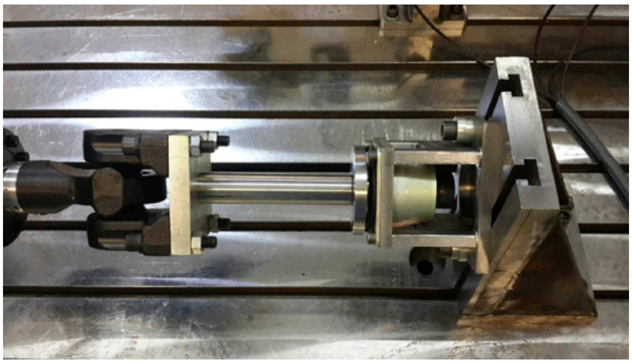

Fig. 4. RLD program test setup.

3. Results and conclusion

3.1. Specimen level test results

Specimen level results play an important role in this calculation method. To increase the precision of the proposed method, number of specimen level tests may be increased. In present study four-arm shear specimens were tested at mentioned test parameters. Test results are shown in Fig. 5. Three specimens were tested for each strain level and average values are plotted in the figure. Table III shows the UD values, which were calculated by using Wöhler diagram as input and the Eq. (1). UD values for un-tested strain levels were calculated with the help of the trend curve, which was shown in the graph.

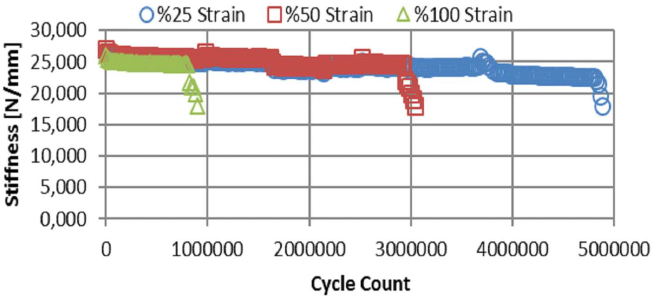

Fig. 5. Specimen level test results. Static stiffness vs cycle count.

TABLE III

Unit damage results.

Strain level [%]	Cycles until failure [N]	UD
25	4860000	2.058×10^{-5}
50	3020000	3.311×10^{-5}
100	880000	1.136×10^{-4}

3.2. Product level test results – numerical approach

Numerical calculation method uses the UD values and level crossing diagram as inputs of life-time prediction equation. Sampling rate of RTLS is not important, because a unitless term $\mathrm{rep}_i/\mathrm{TP}$ is used in Eq. (2) to nullify the effect of sampling rate. Level crossing and calculated damages according to UD values were listed in Table IV.

TABLE IV

Level crossing and damages.

Strain level	Nr. of points	Calc. UD [$\times 10^{-5}$ %]	Strain level	Nr. of points	Calc. UD [$\times 10^{-5}$ %]
0.667	1	4.74	−0.115	269	1.69
0.556	105	3.73	−0.281	106	2.22
0.654	264	4.61	−0.376	39	2.63
0.559	70	3.76	−0.434	30	2.93
0.500	71	3.33	−0.477	11	3.19
0.498	63	3.32	−0.516	15	3.44
0.089	54	1.63	−0.559	25	3.76
0.482	58	3.22	−0.654	38	4.61
0.404	29	2.77	−0.556	128	3.73
0.134	91	1.75	−0.667	139	4.74

Initial static stiffness in axial direction was around 2000 N/mm. It corresponds to rubber compound described in Table I. The values in Table III were used to calculate the life time prediction for selected cone mount. Equation (2) was used to calculate the life time prediction with selected RTLS. Results are listed in Table IV. Target limit for static stiffness change, according to initial values, was defines as 20% and according to the prediction, 80.3 s RTLS which has the level crossing numbers in Table IV, will damage the part after ~ 1000 cycles.

After the completion of the test, the estimation of static stiffness change will be around ~ 21.09%. Figure 8a shows the RLD Program results. RTLS was applied to cone mount element in axial direction and the static stiffness measurement was repeated for each 50 cycles. Test results show that 20% limit was passed after 900 cycles of RTLS. This result matches the prediction with an error of less than 10%.

3.3. *Product level test results – FEA approach*

In the proposed method the numerical approach shows a good correlation with our other approach based on FE, where one can use two different damage models. Discontinuous and continuous damage models can simulate this situations. For both methods we need to define the model coefficient by using the curve fitting tools in MSC Marc software. Gathered values, which are shown in Fig. 6a and b, were used for curve fitting and calculation of the damage material coefficients. Discontinuous damage required a progressively increasing strain levels. The calculated values are listed in Table V.

TABLE V

Unit damage results from FEA.

Strain level [%]	UD
25	1.968×10^{-5}
50	3.254×10^{-5}
100	1.687×10^{-4}

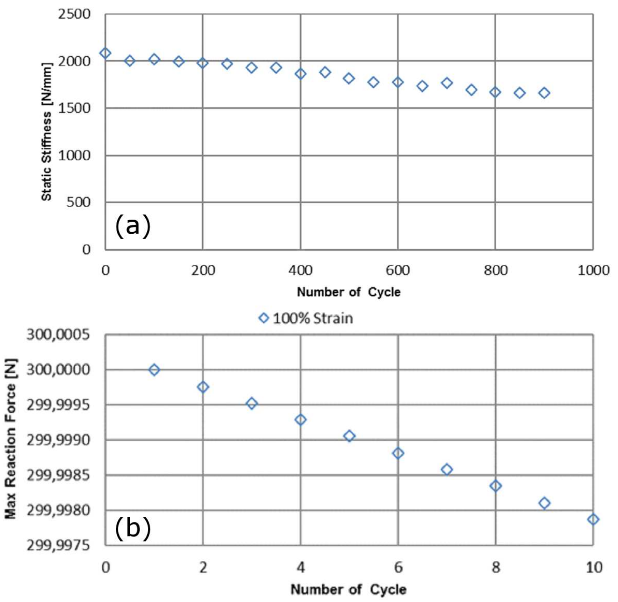

Fig. 6. (a) RLD program test results, (b) FEA max. force decreasing curve.

TABLE VI

Expected RLD program results on product level test.

Strain level	Calc. TD[%]	Strain level	Calc. TD[%]
0.667	0.029	0.115	0.284
0.556	2.196	0.281	0.293
0.654	6.064	0.376	0.191
0.559	1.147	0.434	0.219
0.500	0.884	0.477	0.109
0.498	0.651	0.516	0.193
0.089	0.219	0.559	0.410
0.482	0.349	0.654	0.872
0.404	0.100	0.556	2.678
0.134	0.099	0.667	4.100

On the other hand, the continuous damage model requires a cyclic strain to be always at the same level instead of the progressively increasing one [10]. The paper in this research reports the application of continuous damage because specimen level tests were carried out at different constant strain levels in individual tests. Ogden material model with continuous damage parameters was used to simulate the damage status in the present study. Stress decay was observed in different strain levels on specimen level samples and again Wöhler diagram was created as a result of FEA study.

The obtained UD values were used to make a life time prediction identically with the numerical approach. UDs were calculated from Eq. (3) and are listed in Table VI. When the same method is applied to cone mount by using FEA UD values, according to the prediction, 80.3 s RTLS which has the level crossing numbers in Table IV, will damage the part after ~ 1062 cycles. After the completion of the test, estimation of static stiffness change will be around $\sim 20\%$. Test results show that the 20% limit was passed after 900 cycles of RTLS. This result matched the prediction with 18% error.

4. Conclusions

The aim of the present study is to propose a practical method for industrial usage, which can be driven by both the numerical approach and the FEA. The study and the results show that the proposed method can be used for product development activities with 10–18% deviation from real test results. FEA approach is the final aim of the complete study and it is a natural result for numerical approach. When the numerical approach is applied to any type of rubber compound, results can be used for FEA calculation in further development activities. Precision of the proposed method can be increased by using more specimens during specimen level tests. Discontinuous damage model is a usable approach for FEA calculation to make life time predictions.

Acknowledgments

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References

[1] Ö. Karaçalı, *Acta Phys. Pol. A* **131**, 457 (2017).

[2] Ö. Karaçalı, *Acta Phys. Pol. A* **127**, 1167 (2015).

[3] Ö. Karaçalı, *Acta Phys. Pol. A* **127**, 1195 (2015).

[4] C.S. Woo, H.S. Park, W.D. Kim, *The Effect of Maximum Strain on Fatigue Life Prediction for Natural Rubber Material*, 2013.

[5] T.Z. Ghalami, Ph.D. Thesis, The University of Toledo 2013.

[6] A. Gent, *Engineering with Rubber*, 2nd Edition, Carl Hanser Verlag, Munich 2001.

[7] C.S. Woo, W.D. Kim, J. Kwon, *Mater. Sci. Eng. A* **483-484**, 376 (2008).

[8] V.L. Saux, Y. Marco, S. Calloch, C. Doudard, P. Charrier, *Int. J. Fatigue* **32**, 1582 (2010).

[9] J. Diani, B. Fayolle, P. Gilormini, *Eur. Polymer J.* **45**, 601 (2009).

[10] Mar-103, Experimental Elastomer Analysis, MSC Software Corporation.