Chapter 8. Conclusions and Future scope

This thesis primarily concentrates on the influence of the bi-nonlinearity on the characterization of Mode I fracture and fatigue behaviour of a cracked giant magnetostrictive material in the coupled magneto-elastic field. A hysteretic coupled magneto-thermo-elastic nonlinear constitutive relations have been derived to properly characterize the material behaviour. In addition, some experimental and numerical analysis related to fracture and fatigue mechanics have also been performed on the Terfenol-D SENB specimen. Appraisal and concluding comments are provided for the current work in this chapter, which bodes well for the construction of a sound design philosophy for devices based on large magnetostrictive materials.

8.1. General conclusions

Giant magnetostrictive materials (GMM) exhibit nonlinear magneto-thermo-elastic coupling phenomena and possess some attractive magneto-elastic properties and finding potential applications in sensors and actuators field. However, the attractiveness comes with a cost, that the Terfenol-D is an expensive alloy and challenging to manufacture owing to the high reactivity of its constituent elements and impurities. The biggest drawback of Terfenol-D is its extremely brittle characteristics, and in the presence of manufacturing flaws, it has a substantially lower tensile strength than its compressive strength. The giant magnetostrictive material based intelligent devices are widely used in industries such as automotive, avionics, and construction engineering. The dynamic forces generated by these kinds of industrial applications could cause undesired operating circumstances and structural vibrations in intelligent devices. So, the high level of brittleness, low tensile strength, manufacturing flaws, and unwanted operating conditions limit the broader use of Terfenol-D based smart sensing devices in such industries and make them prone to in-service fatigue-fracture failure, particularly in the presence of a magnetic field. The failure and fracture pattern which might be considered stochastic in nature to predict with certainty can therefore compromise its performance. Thus, it is critical to analyze the performance of GMMs under such circumstances and to provide a method for estimating magnetostrictive device service life.

This analysis constitutes the development of a generalized coupled field vector model to study the magneto-thermo-elastic response with applicability to 1D, 2D and 3D domain of giant magnetostrictive materials (GMM). The nonlinear hysteretic constitutive descriptions are based on the sound thermodynamic theory incorporating the coupling in three dimensions. The material constants associated with the proposed model can be calibrated from physical and experimental evidence. The constitutive relations are derived for bulk magnetostrictive materials of arbitrary shape and size, such as films and rods. Finite element based numerical simulations are carried out to assess the hysteretic magnetostriction and magnetization responses efficiently under the effect of a wide range of prestress and ambient temperature. The proposed model is generalized by incorporating a novel vector function of the hyperbolic tangent to accommodate the nonlinear elastic strain, which is built on the knowledge of isotropic elasticity theory and the physical facts of volumetric strain due to magnetostriction. A vector generalization approach for the J-A model to three dimensions is used for capturing the magnetic hysteresis that arises due to the pinning of magnetic domain walls. Then, the results of the theoretical model have been compared in certain cases with available experimental literature for the giant magnetostrictive material Terfenol-D, and the variations are consistent enough to validate the model. The observed asymmetries of the hysteretic magnetization, magnetostriction and stress vs. strain curves are critically analyzed, citing the physics of magneto-elastic material. Also, the influence of demagnetization for field problems have been discussed and are of relevance for investigating the effect of demagnetization sources. The constitutive descriptions are found to describe qualitatively and quantitatively the inherent vectorial hysteretic nature, stress anisotropies for a wide range of prestress levels, temperature effects and the variability in Young's modulus (*ΔE* effect). The average normalized root mean square error and the maximum errors are found to be within the range of [1.05 to 2.8] and [2.3 to 7.6], respectively. The discrepancies in inner loops as shown in **Figure 14** for the case of giant magnetostrictive material with quasi-static and low frequency operation is found to be small enough to affect the response characteristics. In the light of above demonstration with the observations presented, this might lead to future work with full scale implementation of reversal curves to the proposed nonlinear vector hysteresis model. The asymmetries of predicted results also indicate the significance of considering the effect of demagnetizing field and the Weiss molecular field on the nonlinear characteristics of magnetostrictive materials and gives a sound basis to explain the uncertainties and discrepancies of the response characteristics for the design and development of magnetostrictive smart devices.

After developing the nonlinear hysteretic constitutive model, an appropriate experimental and numerical analysis is conducted to determine the magnetostrictive material properties of procured Terfenol-D specimens needed to use in the proposed constitutive model for numerical fracture characterization. Physics-based experiments has been conducted to characterize the hysteretic magnetic response for stress-strain, magnetization and magnetostriction loops. Terfenol-D magnetization and magnetostrictive properties are sensitive to magnetic and mechanical bias conditions; therefore, a precise finite element based model has been created. Then numerical analysis is performed to calibrate the material parameters for the proposed constitutive model consistent with the experimental hysteretic magnetic response curves.

Then, a new expression of conservation integral $J_1(s)$ for a mode I crack has been proposed to have the physical meaning of energy release rate (both in two dimensional and three dimensional cases) for a homogeneous, isotropic giant magnetostrictive material considering combined effects of inertia, thermal and magnetostriction effect. An experimental and numerical study has been conducted to evaluate the influence of the bi-nonlinearity on the characterization of Mode I fracture behaviour of a cracked giant magnetostrictive material in the coupled magneto-elastic field. The experimental study was first conducted to investigate the crack extension behaviour of notched Terfenol-D specimens under three-point flexure loading in the absence and presence of a magnetic field. Then the Weibull statistical theory of strength is utilized to estimate the peak fracture load data. Finally, a finite element study was conducted to evaluate the three-dimensional path independent J-integral as a critical fracture parameter in a magneto-elastic field. Based on the results drawn from the combined experimental and numerical study, some specific conclusions can be summarized as:

1. The bi-nonlinear stress-strain behaviour of the Terfenol-D in the coupled magneto-elastic field is approximated with a novel hyperbolic vector generalized magneto-thermoelastic constitutive model. The material parameters are optimized using numerical simulations and physics-based experiments. Different bi-nonlinear stress-strain behaviour is observed in the absence and presence of the applied external magnetic field.

2. An adequate quantity of Terfenol-D SENB specimens is tested for fracture characterization with and without a magnetic field. The results inferred that Terfenol-D fractured at a lower load under the applied external magnetic field, and the peak

fracture load data varied over a range due to the uncertain tensile strength of Terfenol-D.

3. The two parameter Weibull statistical distribution is plotted for the peak fracture load values and cumulative probability of failure. The mean peak fracture load is determined using the least square method (LIN2), biased and unbiased maximum likelihood estimation (MLE2-B & MLE2-U) approach. The mean values 54.134 N and 46.616 N obtained from the MLE2-U estimator in the absence and presence of a magnetic field, respectively, are used for the calculation of the experimental and numerical critical strain energy release rate parameter $\mathrm{J_{Ic}}$.

4. According to ASTM E399, only the mean fracture load values are considered in the evaluation of the experimental fracture parameter $\mathrm{J_{Ic}}$, not the specimen's load-displacement characteristics. As a result, discrepancies arise when bi-nonlinearity is taken into account.

5. The average values of critical strain energy release rate (J_{Ic}) evaluated numerically are found to be 16.875 N/m and 15.820 N/m in the presence (0.03 T) and absence of external magnetic field respectively. The experimental J_{Ic}value based on the area under the load vs displacement curve of the SENB experiment is determined as 17.31 N/m while applying the magnetic field and 15.45 N/m without the application of external magnetic field. This validates the appropriateness of the proposed bi-nonlinear constitutive magneto-elastic model.

6. The appropriate form of the 2-D and 3-D J-integral is formulated and the same has been implemented through a C-program code of the general $\boldsymbol{H}(\boldsymbol{M})$ and bi-nonlinear stress-strain relation in the finite element program. The 2-D and 3-D J-integral is evaluated on the thirteen different contours for the bi-nonlinear stress-strain field

under the magneto-elastic domain. The excellent degree of path independence of all contours illustrates the authenticity and efficacy of the model.

7. The 2-D plane strain J-integral and 3-D J-integral values are significantly different from the experimental fracture parameter $\mathrm{J_{Ic}}$ due to bi-nonlinearity. The 3-D J integral values are greater at the mid-plane of the specimen than near the free surfaces because the plane-strain condition is assumed to be predominant. In an external magnetic field, the 3-D J-integral is estimated to be greater owing to more ascendant plane-strain state.

8. The 2-D plane strain J-integral values are substantially different from the 3-D J-integral values owing to the three-dimensional effects. This difference increases with the application of external magnetic field as for the larger deformations the actual stress-strain state in the finite specimen considerably differs from that in an assumed infinite thick specimen. Thus, the three-dimensional assessment is believed to be essential to a finite-thick SENB specimen.

Hence, it is beneficial to consider the nonlinear magneto-elastic effects in determining the 3-D critical energy release rates (J_{Ic}) rather than to get the J_{Ic} from the peak fracture load, which has been the standard method for most cases involving fracture-dominant failures. Finally, a combined theoretical and experimental study has been conducted to understand the influence of magnetic fields on the cyclic fatigue behavior of Terfenol-D. Based on the results drawn from the combined study, some specific conclusions can be summarized as:

1. The number of cycles to failure of Terfenol-D under magnetic fields was smaller than that under zero magnetic field when identical load, load ratio and cycle frequency conditions are maintained.

2. By using the finite element techniques, a log-log plot is created between the sensitivity of the growth rate (da/dN) and strain energy release rate range ΔJ. Then, by linear curve fitting techniques, the updated Paris law for the Terfenol-D specimens under fatigue loading at load ratio $R = 0.1$ and frequency $f = 10\ Hz$ in the presence and absence of magnetic field are determined. The sensitivity of growth rate (da/dN) to the change in strain energy release rate range ΔJ in the presence of a magnetic field is markedly higher than in the absence of a magnetic field.
3. The numerical fatigue life of Terfenol-D SENB specimens is predicted for different maximum cyclic load levels. An experimental analysis is conducted to validate the predicted numerical life. The numerically evaluated data for fracture loads with the number of cycles spent show a good agreement with the experimentally evaluated data.

Hence, it is beneficial to consider the nonlinear magneto-elastic effects in predicting the fatigue life of giant magnetostrictive materials.

8.2. Future scopes

This research provided a method for the characterization and evaluation of the fatigue and fracture parameters of giant magnetostrictive material in the coupled magneto-elastic field. Efficient and optimized mathematical model and finite element frameworks are demonstrated for analysing the failure behaviour of giant magnetostrictive material due to fatigue and fracture. Precise experimental techniques are presented for the validation of numerical results. Following is a list of potential future initiatives that might utilise this study as a starting point:

1. The generalized coupled field constitutive model for 3-D hysteresis response can accommodate small hysteresis loops and inner symmetric loops with some

discrepancies but lead to predicting errors for high-order reversals. This is a limitation of the proposed mathematical model. A better vector generalized hysteretic constitutive model can be developed to get around this problem.

2. The experimental and numerical study for Mode I fracture parameter characterization of a cracked giant magnetostrictive material is considered only 0.03 T magnetic field level for reference study owing to the expensiveness of material and high cost involved in the specimen preparedness. This study can be extended to include the analysis of the complete operating range of the giant magnetostrictive material.
3. Experimental and numerical analysis for fatigue strength characterization and life prediction of giant magnetostrictive material is conducted only with a limited number of samples. A more robust analysis can be conducted using adequate specimens and probabilistic techniques.
4. The fatigue analysis is only limited to a constant load ratio $R = 0.1$, low cycle frequency $f = 10\ Hz$ and magnetic field level 0.03 T. The accuracy and reliability of this analysis can be improved by varying these parameters judiciously. However, it will require an efficient experimental setup that can perform such sensitive analysis at different load ratios and for low to high loading cycle fatigue.
5. The experimental and numerical fatigue and fracture study for a cracked giant magnetostrictive material are only limited to the magneto-elastic domain. However, intelligent devices based on giant magnetostrictive material also undergo variable thermal environments. The challenge will be in future to perform a well-controlled experimental and numerical study for fatigue and fracture strength analysis for such materials in the magneto-thermo-elastic domain.