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*Research Article*

# Reconstruction of load histories using strain gauges

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**_Abstract_**

*Off-highway construction equipment sees structural loads of varying magnitude during their life. Load cases used in Finite Element Analysis (FEA) often tend to be conservative due to uncertainty in load directions and magnitudes. For cost-sensitive markets like India, the overdesign caused by such load cases tends to shadow the product's market competitiveness. There is an increasing need of developing and using 'optimal' load cases during design. Method of 'Load Reconstruction' holds promise in this regard. It generates load estimates using strains; exactly the reverse of what an FEA does. It makes use of existing strain gage data to generate these loads using certain mathematical calculations. In the present Study, manual gear shift lever of an off-road vehicle is considered. Using the 'Load Reconstruction' technique upon the field test data, operator hand loads during actual gear-shifting are generated.*

***Keywords:*** *Optimal load cases, Load Reconstruction, Finite Element Analysis (FEA)*

## 1. Introduction

For fatigue evaluation of any component of the system, it has to take a count of scatter of components geometrical behavior, material properties/behavior and service load behavior acting on the component. Scatter of component geometry and component material is basically because of manufacturing process and material resource. At the other side service loading on the component decisively depends on various parameters like operating conditions, environmental conditions, user usage and working conditions. One of the most important design considerations an analyst or designer must take into account is the in service loading that the component will see. In a typical FE analysis, the in-service load history is known and applied to the FE model to create the stress and strain history of the component for further analysis. This typical FE analysis workflow is shown in Fig.

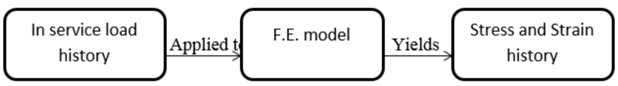


**Fig.1** Typical F.E. analysis workflow

For some components, especially those with complex operating environments, the in-service load history can be very difficult to directly measure and/or accurately predict. One can measure these load histories with the aid of load transducers. For example, fitting a prototype of the component with a load transducer. This may take a significant amount of time and money and, more importantly, it can physically alter the component by changing its mass, stiffness, and load path. These physical changes could produce inconsistent results between the measured loads and the actual loads. What was find that most of the time the complexity of geometry of a part make it impossible to completely separate out individual load effect.

One way to work around these obstacles is to use an FE model solved with unit loads and the resulting strain response to calculate a strain transfer matrix. The strain transfer matrix is a matrix that relates applied loads to strain response of each leg. Once calculated for the unit load case on the FE model, it can be used in conjunction with measured in service strain histories to back calculate the in service load history. It is possible to take a gauge and using that gauge output to predict loads going in that part. We don't need to put an external transducer to the system but rather just put gauge on particular part and transmit it in to a transducer. Doing this effectively turns the entire component into its own load transducer. This back calculated load history can then be used as a realistic input to the FE model, or as a loading profile for laboratory testing.

For this method the unknown factor is not the in-service strain history but the in-service loading history. The FE analysis workflow used to back calculate the unknown in-service loading is shown in fig. below,

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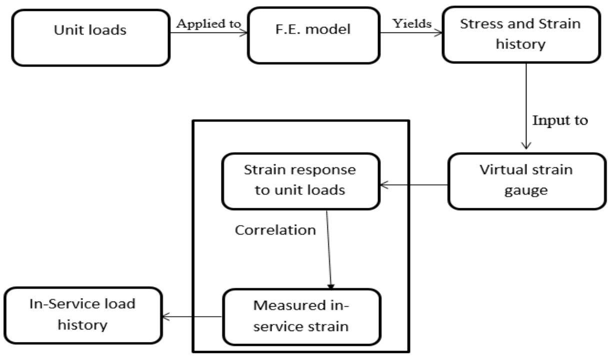


**Fig.2**Workflow used to back calculate in-service loading from known in-service strain history

It should be noted that this type of load reconstruction calculation requires the following assumptions to be made:

1) The component operates solely in the material's linear elastic range.
2) The locations and orientations of the physical and virtual strain gauges match as closely as possible.
3) The physical and virtual strain gauges are approximately the same size.

Additionally, it is important to point out that to make the load reconstruction possible, there must be at least as many independent strain measurements as there are loading degrees of freedom to be reconstructed.
This study proposes the new technique for load measurement rather use of load cells/transducers. Gear shift lever of an off-highway vehicle has been considered for this study.

## 2. Strain Recording

Actual strain histories are recorded using strain gauges for similar system under similar working conditions. Strain has been recorded for the no. of possible operations on the system. Off highway vehicles gear shift lever would be subjected to various operations like shifting gears, transport on rough terrain and transport on normal roads. These strains have recorded at three different locations with three different gauges. The location of strain gauges on gear shift lever shown below in the fig.3. Strain histories are then utilized for reconstruction of load histories using FE analysis and nCode.

Among all the operations for which gear shift lever would be subjected to loading, dynamically shifting gear is the most damaging operation.Strain histories recorded for the dynamically shifting gear operation have been shown below. These strains are recorded for the specific time period. This time period varies as per the company practice. Every automobile company has its own test schedule for the different kind of operation which is the results of market survey and many years of experience.

**Fig.3** Mounting of strain gauges over gear shift lever

### *2.1 Strain data for dynamically shifting gear operation*

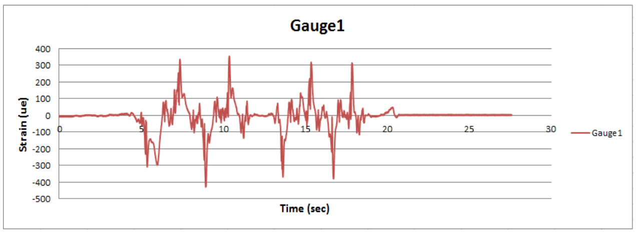


**Fig.4**Strain data recorded at gauge1 location

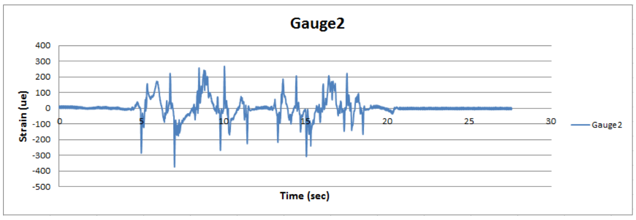


**Fig.5** Strain data recorded at gauge2 location

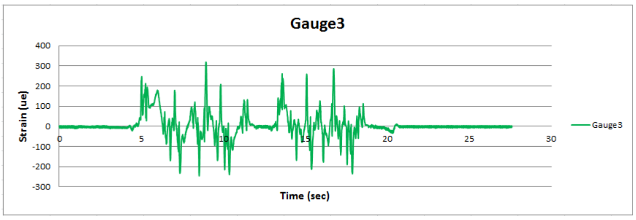


**Fig.6** Strain data recorded at gauge3 location

## 3. FE Method

### *3.1 CAD model*

Gear shift lever which is the part of manual transmission system of off-highway vehicle has been considered for the study. The gear shift is the part of the gearbox which has the shift forks and allows the contact from the driver to the synchronization and they make it possible to choose the gear /gear ratio and to switch this in or out. The system considered for study encompasses of outer tube, inner tube, box plate for holding the outer and inner tube, nut bolt for the clamping the box plate with the part of transmission housing and the plastic knob at the top end of outer tube to ease the gripping so operator can easily manipulate. Plastic knob also called as gear knob, shift knob or gear shift knob. Typically the gear knob includes a diagram of the shift pattern of the gear selection system; i.e. the positions to which the gear stick should be moved when selecting a gear. All these parts are modelled using Pro-E, one of the CAD modelling packages. Below figure shows the creoparametric model of gear shift lever.

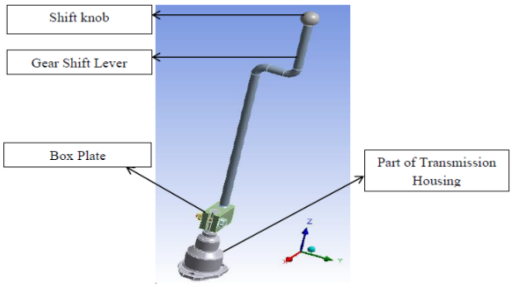


**Fig.7** CAD model of gear shift lever

*3.2 Loading and Boundary conditions*

Gear shift lever is bolted to the transmission housing part, so all degrees of freedom at the bolt location are blocked, (shown in fig. below location 1, 2, 3). Effect of bolt preload is nullified as it affects the load histories that to be reconstructed. As the strain gauges are applied at the locations which are sensitive to the bolt preload, it measures the strain due to bolt preload too, but one doesn't want to measure the preload strain so bolt pretension is nullified by making bonded contact. Load is applied at the shift knob by user/operator, shown in fig. Magnitude and direction of load is unknown and that's the thing that one is interested to find out.

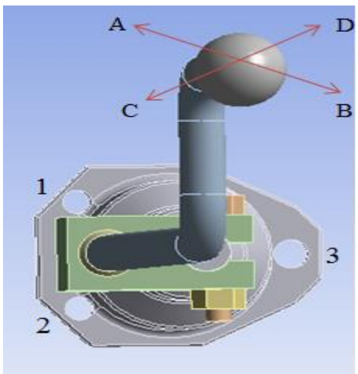


**Fig.8** Top view of the gear shift lever

*3.3 F.E. analysis using Ansys Workbench*

As far as this study considered, Ansys workbench 14.5.7 has been used for static structural analysis of gear shift lever. To make load reconstruction successful, the component must operate solely in the materials linear elastic range. This condition is true for gear shift lever operations. Gear shift lever has to be analyze for linear elastic static structural condition. Linearity of the model under loading situations is maintained by making large deflection off in Ansys workbench. Bolt pretension effect also nullified by making contacts bonded. Now the main obstacle came in way is that how much and in which direction load should be applied to carryout F.E. analysis? Let us justify this taking an example of hand break in four wheel vehicle. Suppose one has the strain data recorded duringthe application of hand break and he is interested to find out the load data. Immediately he will think about the magnitude of load instead direction because he knows that the direction will always be vertical.

Now just think about the gear shift lever, operator applies the load at shift knob in a horizontal plane that is(X-Z plane). One don't know the direction of load. Applied load may be in X direction, Z direction or may be inclined to X and Z direction, but there is always component of load along X and Z direction. If the load applied is purely along X direction then component along Z direction is zero and vice versa. If load is inclined then there will be fraction of load along X and fraction of load along Z direction. So if you could reconstruct the load along X and Z direction, you will get the resultant load and direction also.

So, now direction along which load is to be applied has fixed, but question is how much? For load reconstruction process it needs to have model solved with unit load. Is it feasible? Answer is no. Unit load is not physically significant. Rather one could solve the model for 1000N. The strain output for 1000N load can be converted in to strain output for unit load by scaling the 1000N strain by (1/1000) factor, as model is solved for linear elastic condition.

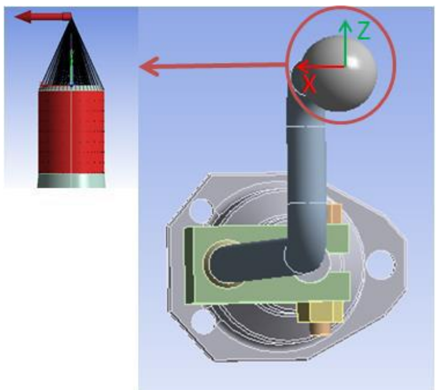


**Fig.9** Remote load applies at remote point in place of shift knob

After F.E. analysis Max principal and min principal strains for 1000N load along X direction and 1000N load along Z direction are obtained.

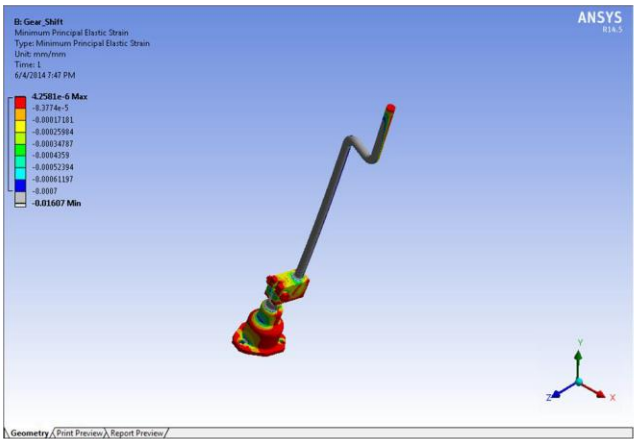


**Fig.10**Minimum principal strain for 1000N load along X direction

These results are plugged to nCode for load reconstruction. This is done by importing the output file that is (.rst file) of Ansys in the nCode.

## 4. Reconstruction of load histories using nCode

### *4.1 nCode*

nCode GlyphWorks is a powerful data processing system for engineering test data analysis with specific application to durability and fatigue analysis. Designed to handle huge amounts of data, GlyphWorks provides a graphical, process oriented environment. Users can simply create an analysis workflow by 'dragging and dropping' analysis building blocks. In addition to general signal processing, GlyphWorks provides leading fatigue analysis capabilities for measured data. Unique capabilities include the ability to help specify accelerated durability tests, saving both time and money in environmental qualification and product validation.

### *4.2 Virtual Strain Gauge*

Virtual Strain Gauge is a standard feature of DesignLife that provides a uniquely powerful way of extracting stress or strain from finite element results. These can be graphically positioned and oriented many single or rosette gauges on finite element model in the FE Input glyph. Gauges can be positioned at either an element centroid or at a node location. A Virtual Strain Gauge glyph is provided to combine loading information and material data to export the stress or strains from the specified strain gauge locations. If the model has been properly meshed, loaded, and constrained, the predicted virtual strain from Design Life will correlate with the measured strain.

### *4.3 Load Reconstruction*

Load reconstruction glyph is specially encrypted glyph for purpose of reconstruction of load histories. The detailed working background of this glyph is explained next.

The relationship between input load and elastic strain response can be extract in this way,

$$\begin{bmatrix} StrainTransfer \\ Matrix \end{bmatrix} \begin{Bmatrix} InService \\ Loads \end{Bmatrix} \equiv \begin{Bmatrix} MeasuredService \\ StrainResponse \end{Bmatrix}$$

Where the strain transfer matrix is a matrix that consists of the strain response to unit load inputs , the in service loads is a column of load magnitude and strain response is a column of resulting strain magnitude. This equation says that within the linear elastic regime, any strain response must be a linear combination of the input loads. Since the unknown and desired value in this equation is the in service loads. Therefore Solving this equation for the in service loads gives the following,

$$\begin{Bmatrix} InService \\ Loads \end{Bmatrix} \equiv \begin{Bmatrix} MeasuredService \\ StrainResponse \end{Bmatrix} \begin{bmatrix} StrainTransfer \\ Matrix \end{bmatrix}^{-1}$$

Note that the accuracy of the result is highly dependent on the condition of the strain transfer matrix. A well-conditioned strain transfer matrix is required for the inversion process. At the very least, this matrix must have as many measured strains as there are loads.

Now before proceeding to the load reconstruction, thing is that we have solved the F.E. model for 1000N load in Ansys but to make the load reconstruction successful it needs to provide the strains calculated for unit load. So it is essential to convert 1000N strain load in to the unit load strain. This can be done by multiplying the 1000N strain by (1/1000) factor, as F.E. model analyzed for the linear elastic conditions. It is possible to convert 1000N strain in to unit load strain by use of linear interpolation. Virtual strain values recorded at the gauge locations by virtual strain gauge glyph for 1000N load are shown in the table below

**Table 1** Virtual strain value for 1000N load at gauge locations

| | Virtual Strain | | |
|---|---|---|---|
| | Gauge1 | Gauge2 | Gauge3 |
| | uE | uE | uE |
| 1000N along X | 1631 | -881 | -844 |
| 1000N along Z | -8.86 | 1418.5 | -1385.5 |

**Table 2** Virtual strain value for unit load at gauge locations

| | Virtual Strain | | |
|---|---|---|---|
| | Gauge1 | Gauge2 | Gauge3 |
| | uE | uE | uE |
| Unit load along X | 1.631 | -0.881 | -0.844 |
| Unit load along Z | -0.00886 | 1.4185 | -1.3855 |

Above tables are also called as strain transfer matrix, that shows the values of each leg of strain gauge rosette with respect to the loading. Now we are with the strain transfer matrix for unit load. After completion of run load histories have been generated for the dynamic shifting operation.

## 5. Result

After completion of run load histories have been generated for the dynamic shifting operation. It has been shown in the following figures.

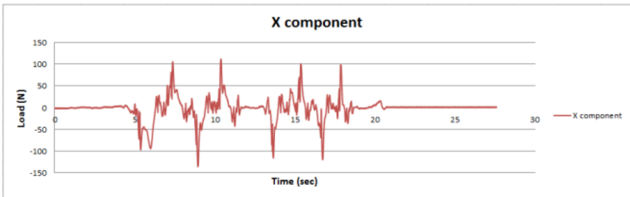


**Fig.11** X component of loading

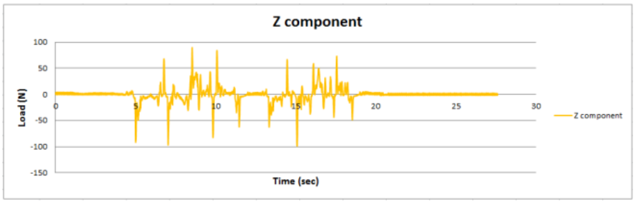


**Fig.12** Z component of loading

From the resultant loading one can make conclusion about the maximum, minimum and average loading on the component.

Loading profile for the dynamic shifting gear operation can be extracted by plotting X component of loading V/S Z component of loading. Below figure shows the loading profile.

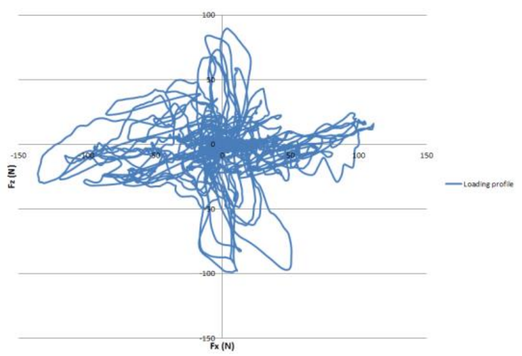


**Fig.13** loading profile of dynamic shifting gear operation

## Conclusion

It can be concluded that, it is possible to reconstruct load histories acting on component using strain gauges rather using load cells or transducers.

## Future work

Strain transfer matrix is must to calculate load histories from available actual strain histories. In this work initially strain transfer matrix for 1000N load was calculated and later it was converted in to unit strain transfer matrix. In the future same procedure repeated for different values of loads in place of 1000N, provided that component doesn't undergo plastic deformation and load histories will be calculated. These predicted load histories are verified by comparing simulated fatigue life for back calculated load histories with fatigue life obtained from actual strain histories at given locations.

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