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Experimental Method for Durability Evaluation of a Chisel Mounted on a Composite Working Implement

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Abstract

Purpose: A chisel mounted on working implement, such as agricultural machinery used in irregular farming conditions, is subjected to highly variable fatigue loading during work. To ensure the safety of the chisel on a working implement for the duration of its service life, fatigue testing must be performed with the proper fatigue test load conditions. In this study, working loads for a chisel were developed by reconstructing loads from strain gage data collected during field tests and used to conduct fatigue tests on the chisel component. **Methods:** FE analysis with nCode software was utilized to select the proper quantity and locations of strain gages for load measurements. A fatigue test was performed to experimentally verify the fatigue strength of the chisel and to evaluate the validity of the load history developed with the load reconstruction technique. **Results:** A strain history for the chisel was obtained from data collected during field tests. The data was filtered for the 14-16 km/h speed range, connected, and merged. The chisel load history was developed using the load reconstruction technique. The resulting load history was expressed as a load spectrum using the rain-flow counting method. **Conclusions:** A fatigue test was conducted on a chisel under a constant load condition with an equivalent load amplitude and number of cycles, as calculated by Miner's Rule for linear damage accumulation. During the fatigue test, there were no cracks at any position. It is concluded that the fatigue test method proposed in this study can be utilized successfully as a durability evaluation method for the chisel.

Keywords: Chisel, Composite working implement, Fatigue load history, Fatigue test, Load reconstruction method

Introduction

A composite working implement consisting of a disc harrow, chisel, and hiller is a multi-use agricultural machine that performs simultaneous tillage and hilling. During cultivation, it is equipped at the three-point hitch of a tractor. Currently, models are being developed that can improve working speeds while still efficiently enabling successive complex operations (Jia et al., 2007; Watts et al., 1984). However, while high working efficiency is necessary, it is critical to ensure that structural strength and service life requirements are met during development through sufficient strength analyses and design verifications.

For structural strength and durability evaluations, load histories are very important parameters. However, they are very difficult to directly measure for working implements. Furthermore, reconstruction of the load history is nearly impossible owing to soil irregularities and complex working conditions. Moreover, a significant amount of time and money is required to perform these measurements, as expensive measuring sensors must be installed at multiple positions.

One commonly used method for obtaining these measurements consists of attaching a torque sensor to the wheel axis of a tractor, recording the rotational torque on the axle during driving, and then calculating

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the load capacity using data for the number of revolutions and radius of the wheel (Collins et al., 1991; Cupera et al., 2011). This method allows measurements to be obtained easily when torque sensors can be installed on equipment axles. However, it requires obtaining precise output efficiency data for the power transmission system to reduce errors. Additionally, because the calculated load is assumed to be the same as the tractive force and is applied to all parts of the working implement, it can differ significantly from the actual loads applied to the working implement. As an alternative, a six-axis load measurement system with multiple load cells has been used for direct load measurement (Park et al., 1991; Kim et al., 1997). This system is installed between the three-point hitch of the tractor and the attached working implements, and allows for determination of the force and moment components in the three axial directions by converting the signal from the six-axis load cell. A motion equation is then used to calculate the loads on the disc harrow, after modeling them as resistances resulting from the soil crushing strength, shear resistance, and soil weight (Ahmadi, 2016). However, no equipment is available that can measure loads on subcomponents such as chisels. In addition, the weight of the device itself presents installation challenges.

Generally, composite working implements, such as the agricultural machine tools that are used in harsh environmental conditions like farmland, are subjected to loads of highly variable amplitudes during work, making them critical components for overall structural strength and durability. To ensure safe operation for the duration of the service life of these composite working implements, structural strength assessments must be conducted through durability testing. It is critically important to measure working loads with field tests. In recent years, many researchers have attempted to obtain high-accuracy load measurements with expensive sensors and data analysis equipment. However, there have been significant difficulties measuring the work loads of actual agricultural machinery resulting from a lack of experience with sensor installation, data processing, and load reconstruction techniques.

In this study, the work load for the chisel subcomponent of a composite working implement was determined with a load reconstruction technique using strain gages. Finite element (FE) analysis with nCode software was utilized to select the proper quantity and locations of the strain gages for load measurement. The strain history measured in the field tests was analyzed to reconstruct the load history of the chisel through application of a load reconstruction technique.

Materials and Methods

Composite working implement

The composite working implement is a multi-use tool that is equipped on the three-point hitch of tractor and performs non-powered tillage and hilling. Its primary components are the main frame, disc harrow, chisel, and hiller, as shown in Figure 1. The chisel has an arm 140 mm wide and 25 mm thick that is connected to a hydraulic cylinder used to move the chisel up and down. The chisel is mounted on the main frame and primarily receives a bending load transmitted from the soil through traction. For efficient operation, the chisel is arranged in a single row located between the front and rear rows of the disc harrow.

FE analysis modeling of chisel

FE analysis was used to calculate the stress distribution in the chisel. A solid element was used in the analysis,

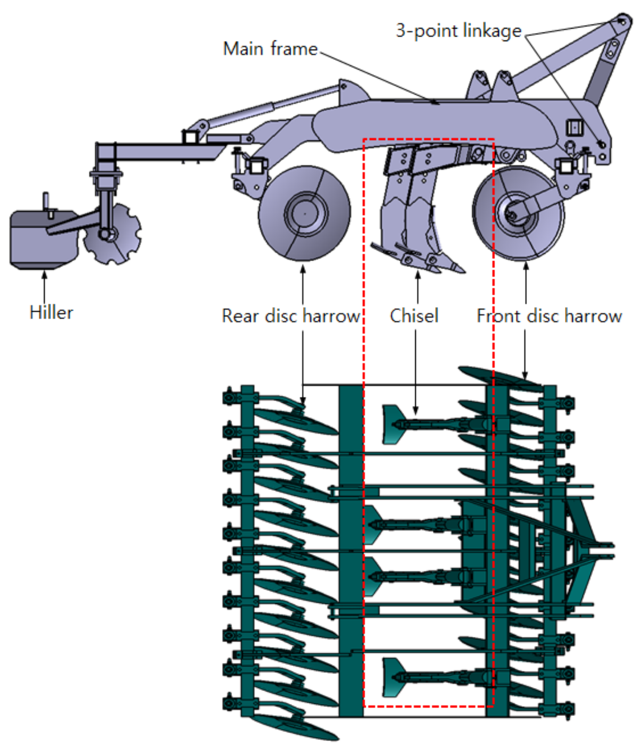

Figure 1. Configuration of the composite working implement.

which was performed with ANSYS R16.0 software. The upper part of the chisel arm that is attached to the main frame was set as a fixed condition in the boundary conditions for the analysis. An x-axis load of 3.0 kN in the working direction was applied to the middle of the lower part of the chisel. Figure 2 shows the model used for the FE analysis of the chisel.

Load reconstruction method

Assuming the load is linearly proportional to the strain in a body with elastic deformation, then the strain, $\boldsymbol{\varepsilon_i}$, at the virtual strain gage locations shown in Figure 3 can be expressed with coefficients A_{ij} by the following relationship for the superposition of the load, L_i:

$$\begin{aligned} \varepsilon_1 &= A_{11}L_1 + A_{12}L_2 \\ \varepsilon_2 &= A_{21}L_1 + A_{22}L_2 \\ \varepsilon_3 &= A_{31}L_1 + A_{32}L_2 \end{aligned} \tag{1}$$

The relationship between the load vector, $\boldsymbol{L}$, and strain rate vector, $\boldsymbol{\varepsilon}$, at all positions can be expressed as the matrix relationship given in Eq. (2) below:

$$\{\boldsymbol{\varepsilon}\} = [\boldsymbol{A}]\cdot\{\boldsymbol{L}\} + \{\boldsymbol{e}\} \tag{2}$$

where $\boldsymbol{A}$ is the strain transfer matrix representing the gage sensitivity of the load and $\boldsymbol{e}$ is the error of $\boldsymbol{\varepsilon}$. If Eq. (2) is rearranged for $\hat{\boldsymbol{L}}$ by minimizing $\boldsymbol{e}$ with the least squares method, Eq. (3) is obtained for estimating the load calculated from $\boldsymbol{\varepsilon}$.

$$\{\hat{\boldsymbol{L}}\} = ([\boldsymbol{A}]^T[\boldsymbol{A}])^{-1}\cdot[\boldsymbol{A}]^{-T}\cdot\{\varepsilon\} \tag{3}$$

Selection of strain gage locations for load measurement

The locations of the strain gages for the load measurement were selected to represent the optimum response points from the stress analysis results. The strain gage location selection was performed using nCode software. This program uses a D-optimal design method to optimize load estimation accuracy by applying algorithms to determine optimal response points. At these points, the strain response is independent of the candidate location where the quantity described in Eq. (3) is at its maximum (Gupta et al., 2015). In this matrix, the variance values, which are the diagonal terms, decrease with increasing number of strain gages, until they converge to a constant value. As these results in increasing load estimation accuracy, the number of strain gages can be determined from the convergence point.

In contrast, a variance inflation factor (VIF) is used to analyze the independence of the load strain responses. The VIF is an indicator of the extent to which the strain response of an arbitrary load is affected by other load responses. For example, a VIF=1 indicates an ideal strain response state that exhibits fully independent response characteristics. To ensure an independent correlation, the number of strain gages must be adjusted so that the value of the VIF is less than 10.

Figure 4 shows the location of three selected strain gages (S1-S3). To assess the reliability of the signals

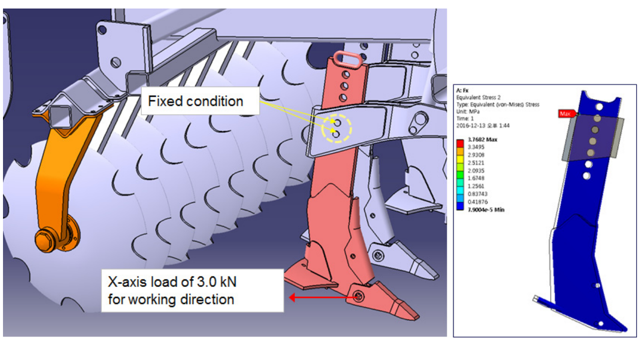

Figure 2. FE analysis modeling of the chisel component.

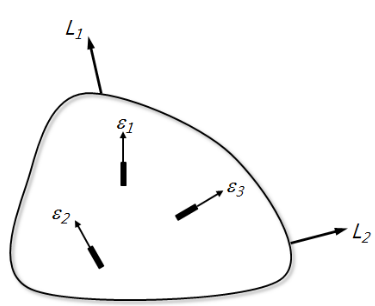

Figure 3. Virtual strain gages and applied loads.

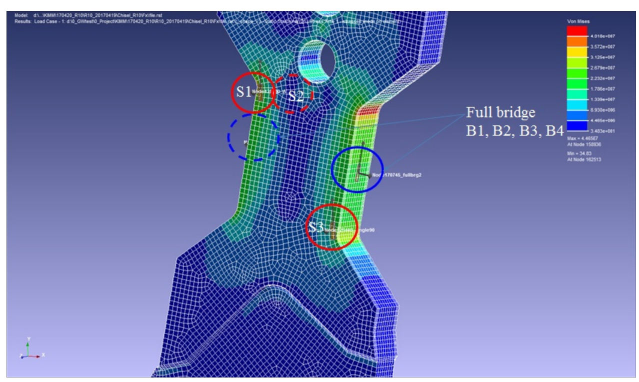

Figure 4. Selected strain gages on the chisel.

measured by these strain gages, full-bridge strain gages (B1-B4) were also attached to the middle of the chisel arm in the direction of thickness. The full-bridge strain gage measurements are responses to bending loads, and are used for comparison with the measurements from strain gages S1-S3.

Results and Discussion

Field test

A 100 hp tractor (model PS100-N, LS Mtron) was used for the field tests, and is shown in Figure 5. Because it was not possible to access outside electric power while the tractor was moving, the internal power of the tractor was used to operate the testing equipment by installing an inverter to convert DC into AC power. Measurements obtained during testing were monitored in real-time over Wi-Fi. A GPS speedometer (model VBSS05, RACELOGIC) capable of measuring speeds of up to 1600 km/h was installed to monitor the driving speed of the tractor. A CCD camera was installed on the rear window of the tractor to verify that the crushing work was being performed properly by the chisel. Measurements obtained by the strain gages during testing were recorded with DAQ equipment (model: HBM). The data sampling rate for the measurements was 300 Hz.

To analyze the soil characteristics of the test area, a cone penetrometer (DIK-5530) and a soil moisture sensor (WT1000B) were used. The average soil cone index and penetration depth were 1939 kPa and 180 mm, respectively. During testing, the temperature and humidity were 26°C and 8.6%, respectively.

Because maintaining a steady tractor speed is difficult, the measurement data from the field tests were collected very irregularly and at various speeds. Therefore, to assess load characteristics as a function of driving speed, the data needed to be analyzed so as to classify response characteristics for varying speed ranges. The speed range observed during the field tests was divided into eight sections, and the measurement data were classified according to the speed section under which they were recorded. These sections were partitioned at intervals of 2 km/h, from 0 km/h to the maximum speed of 16 km/h. Because the chisel moves up and down according to the soil indentations during driving, video from the CCD camera was used to exclude measurements obtained

Figure 5. Tractor utilized in the field tests.

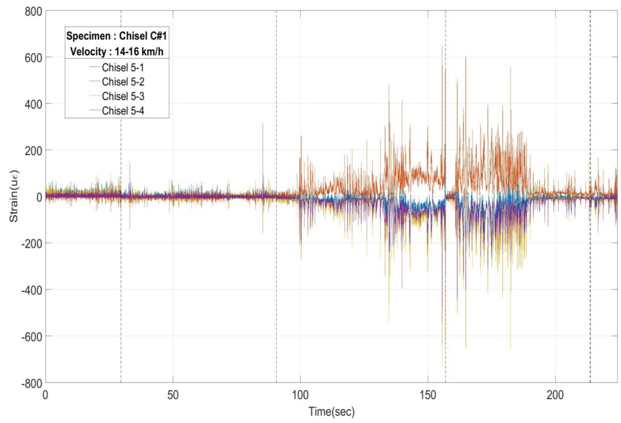

Figure 6. Strain data obtained during the driving test filtered for the data collected in the 14-16 km/h speed range.

from working sections with a plowing depth of less than an 80% of the mean.

Figure 6 shows strain gage data for the chisel obtained during the field tests. The data obtained during the driving test was filtered to include only measurements recorded in the 14-16 km/h speed range, connected, and merged into a single curve. This curve illustrates the representative history of the strain on the chisel during a total of 224 seconds of work within the speed range, and can be used as a basic curve to represent the load history when applying the load reconstruction technique.

Load reconstruction for the chisel

The strain history of the chisel can be used to reconstruct the load history with the load-strain relationship. The relationship between load and strain was obtained by performing a static load test, as shown in Table 1. The strain conversion matrix for the chisel is obtained by calculating the measured strain and substituting for Eq. (1).

$$(\boldsymbol{A})_D = \begin{pmatrix} 0.0166 \\ -0.0189 \\ 0.0191 \end{pmatrix} \quad (4)$$

In Eq. (4), $(\boldsymbol{A})_D$ is the conversion matrix used to convert the measured strain of the chisel into load for the field tests.

By substituting the strains obtained in the field tests, $(\boldsymbol{\varepsilon})_D$, and $(\boldsymbol{A})_D$ into Eq. (3), the chisel load estimation, $(\hat{\boldsymbol{L}})_D$, can be expressed as follows:

$$\{(\hat{\boldsymbol{L}})_D\} = ([(\boldsymbol{A})_D]^T[(\boldsymbol{A})_D])^{-1} \cdot [(\boldsymbol{A})_D]^{-T} \cdot \{(\boldsymbol{\varepsilon})_D\} \quad (5)$$

Figure 7 shows the load history of the chisel, which was calculated using Eq. (5). This curve represents the load reconstructed from the strain data presented in Figure 6. This is the load history calculated by the load reconstruction technique, from the strain histories measured by the three strain gages (S1-S3) attached to the chisel.

Figure 8 shows a comparison of the load history with data obtained from the full bridge (B1-B4) gages. Because loads typically generate bending strain on the chisel, the same behavior is expected from the bending strain signals recorded by the full bridge gages. A comparison of the two curves shows that they have approximately the same load phase, as well as the same load change trends. These results verify the reliability of the load history curve obtained with the load reconstruction technique, as well as the strain data measured during the field tests.

Table 1. Strain results obtained from a static load test for a load of 6 kN

Strain Gage No.	Measured strain ($\times 10^{-6}$)
S1	99.8
S2	-113.1
S3	114.4

Fatigue test

The object of the fatigue test is to experimentally verify the fatigue strength of the chisel and to evaluate the validity of the load history calculated by the load reconstruction technique. Figure 9 is a histogram depicting the load history shown in Figure 7 calculated with a rain-flow counting method. The maximum load is

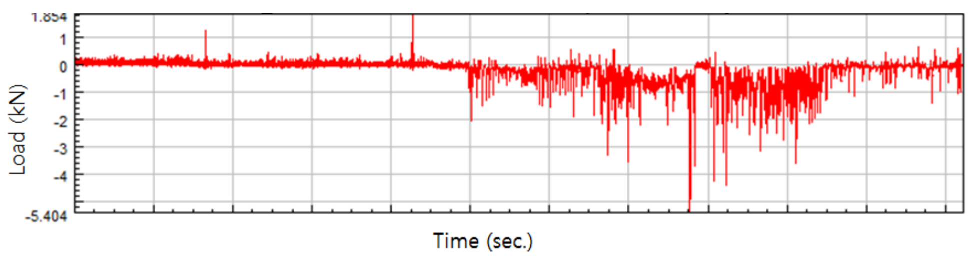

Figure 7. Load history reconstruction for the chisel.

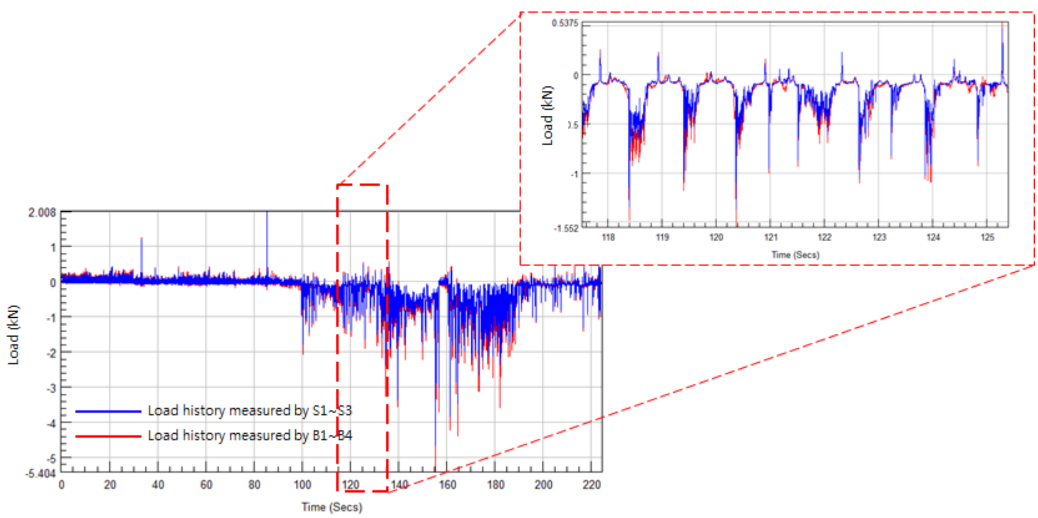

Figure 8. Comparison of calculated load data and bending load data obtained from full bridge gages (B1-B4).

5.25 kN, and loads within the range of 0.25-2.25 kN appear with the highest frequency. Table 2 provides a rain-flow matrix of the chisel load history, including the load range, mean load, and counted cycles.

The fatigue test was conducted under a constant load condition with an equivalent load amplitude and number of cycles, as calculated by Miner's linear damage accumulation method (Miner, 1945). For this test, it is assumed that the target service life is 800 hours with a load frequency of 3 Hz. The required fatigue test time can then be calculated as follows:

$$\text{Test time[h]} = (PD/CD) \times (800[h] \times 3600[h/s] / 224[s]) / 3[Hz] / 3600[h/s] \quad (6)$$

In Eq. (6), PD is the fatigue damage when the chisel is subjected to the load history shown in Figure 7, while CD is the equivalent fatigue damage caused by a constant load amplitude condition. Miner's Rule can be used to determine the number of load cycles required for an equivalent fatigue damage with the S-N curves of the used material. Table 3 lists the calculated fatigue test conditions. Accordingly, the fatigue test was performed for 231,126 cycles, which required a total time of 21.4 hours for a load frequency of 3 Hz, at load amplitudes in the range of 0-5 kN. The load was applied horizontally to the lower chisel plate by a 5-ton hydraulic actuator as shown in Figure 10. Crack inspection was performed with a dye penetration

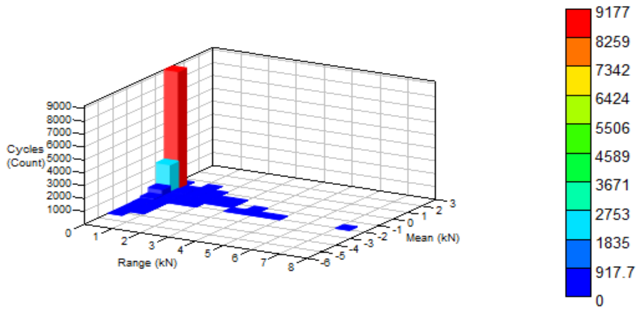

Figure 9. Histogram of load history calculated by a rain-flow counting method.

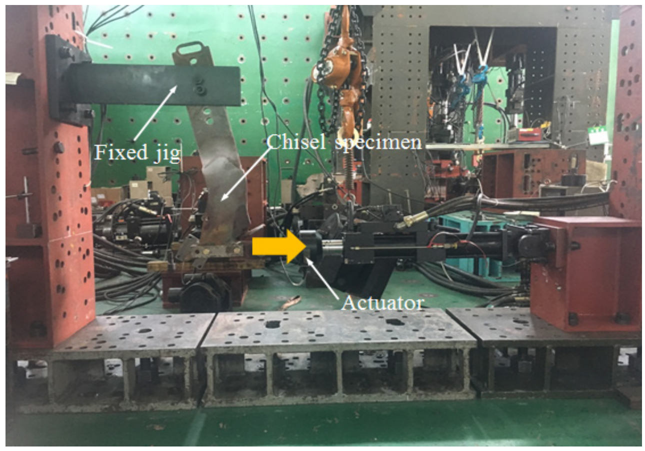

Figure 10. Chisel fatigue test setup.

Table 2. Rain-flow matrix of the load history

Mean (kN)	Range (kN)														
	0.25	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	5.25	5.75	6.25	6.75	7.25
0.47	**9**	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0
-0.09	**9177**	**26**	**5**	**1**	0	0	0	0	0	0	0	0	0	0	0
-0.66	**2215**	**99**	**36**	**13**	**3**	**1**	0	0	0	0	0	0	0	0	0
-1.22	**566**	**42**	**12**	**12**	**11**	**2**	0	**1**	0	0	0	0	0	0	0
-1.78	**168**	**16**	**2**	**1**	0	0	**4**	**1**	**1**	**1**	0	0	0	0	**1**
-2.34	**40**	**3**	0	0	0	0	0	0	0	0	0	0	0	0	0
-2.91	**14**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0
-3.47	**3**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0
-4.03	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3. Calculated chisel fatigue test conditions

	Max. load (kN)	Min. load (kN)	Fatigue damage	Load frequency (Hz)	Test time (h)	Test cycles (cycles)
Load history	1.85	-5.4	[1)] 1.31×10^{-18}		-	
Test load	0	-5.0	[2)] 7.27×10^{-20}	3	21.4	231,126

Note: 1) PD, 2) CD

test after completion of the fatigue test, and no cracks were found at any position on the chisel. This indicates that the fatigue test method proposed by this study can be effective as a durability evaluation method for the chisel.

Recently, multiple researchers have tried to perform high-accuracy load measurements by using expensive sensors and data analysis equipment. However, a lack of experience with sensor installation methods, data processing, and load reconstruction techniques have led to difficulties representing working loads, which is an essential process in the development of agricultural machinery. The load reconstruction technique using strain gage measurements in this study is a technical method for solving these problems, and can be used advantageously for working loads and to assess the durability performance of composite working implements.

Conclusions

In this study, working loads for chisel subcomponents were determined by reconstructing loads from strain gage measurements obtained during field tests of a composite working implement for agricultural machinery. FE analysis with nCode software was used to determine the optimum response point for the maximum strain response, and an appropriate quantity of strain gages was determined to fall within a range where most of the strain responses are ensured to behave independently. In the field tests, signals from the strain gages attached to the chisel were measured. The strain history was obtained from measurement data filtered for the data collected in the 14-16 km/h speed range, connected, and merged. The chisel load history was developed from this data using the load reconstruction technique. The resulting load history was expressed as a load spectrum with a rain-flow counting method. The maximum load was 5.25 kN, and loads with amplitudes in the range of 0.25-2.25 kN had the highest frequency. A fatigue test was conducted under constant load conditions with an equivalent load amplitude and number of cycles, as calculated by Miner's linear damage accumulation method. The results of the fatigue test showed no crack formation at any position on the chisel. Therefore, the fatigue test method proposed in this study can be effectively used as a durability evaluation method for the chisel.

Conflict of Interest

The authors have no conflicting financial or other interests.

Acknowledgements

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