Research on reverse evaluation of the load based on True-Load algorithm

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Abstract: The disagreement between the design load and the real dynamic load acting on a structure must be avoided for quality design and engineering. The real load obtained by a force sensor is only valid for simple problem and often for just a subset of the loading degrees of freedom. Attempting to measure load indirectly by strain gauges is difficult because of the load coupling in strain response of the loading degrees of freedom. True-Load software provides a proven mathematical method combined with the finite element technique to obtain loads from strain measurement. This paper studies a wheel set using this algorithm. The data obtained from this study indicates that the two necessary conditions should be must exist if this method want to be succeed: the finite element model (FEM) must be sufficiently represent the test object; the optimal True-Load locations of the strain gauge must match the actual measured locations of strain gauges. This paper provides some reference values for the reliable application of this load calculation from strain gauge measurement method.

Key words: wheel set；True-Load algorithm；indirect load measurement; influence coefficients；strain gauge

0 Introduction

For vehicles subject to dynamic loading, including high speed Electric Multiple Unit (EMU) trains, the product structure design loads are initially determined by related standards formed on the basis of experience. Often the experience is not reliable and thus the design load specifications are also not reliable. Once the product is in service, the real load and the design load of a structure are often vastly different. This inconsistency in loading will be debated and will lead to issues in product design. Cost will be increased if the design load is higher than the real load. Reliability risk will increase when the real load is higher than the design load. Both of these conditions create unnecessary cost and risk to the companies, consumers and stakeholders.

A method to identify and obtain the load in service reliably and effectively is always a technical problem which needs to be solved urgently at home and abroad. For years, there are two ways to solve this problem: (1) design and layout of special force sensor to identify and obtain loads directly; (2) identify and obtain loads by arranging strain gauges. The direct force measurement may only be used with the situation when a direct relationship between the sensor signal and the operating load can be established. Another limitation is that traditional load transducers are more difficult to install it on the structure. The structure will often need to be modified to mount a direct load transducer and the act of modifying the structure will change the stiffness, mass and load path of the structure. Direct load measurement is only effective in a limited number of applications. General application of traditional load measurement brings significant cost, timing delay and limited ability to capture only a subset of the loads acting on a structure.

In view of the above limitations, a method for obtaining loads by strain gauge is now used at home and abroad. But in fact, it is difficult to obtain the load through the arrangement of the strain gauge indirectly, because there is a deep load coupling in the stain response of the load. Traditional techniques using strain gauges attempt to use first principals of structural mechanics to decouple the strain response of gauges between loading degrees of freedom. An alternative approach of the True-Load software provides a computational method utilizing a fully populated correlation matrix and is combined with the finite element technology. The technology deployed in the True-Load software is traditionally referred to as ‘influence coefficients’. In this paper, we use the algorithm of the software as a tool along with a provided representative set of wheels to study the effectiveness of reverse evaluation of the load. A complete comparison and analysis of the consistency between the real load and the load obtained by the True-Load algorithm will be shown. A discussion of errors is also provided. This study will serve to provide some reference value for the application of this kind of load computation methodology.

1 Basic algorithm Introduction:

For a linear structural system, the linear relation between load, strain and deformation is shown in Figure 1.1.

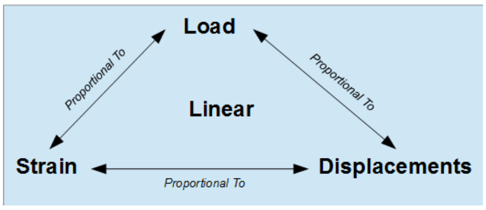

Fig. 1.1 schematic diagram of structure linear relationship

Converting the right hand side of Figure 1.1 to an equation, this relationship can be expressed as equation (1.1). Equation (1.1) is quite simply Hooke's Law.

$$[F]=[K][X] \tag{1.1}$$

From Figure 1.1, the left hand side of the diagram indicates that a strain corollary to equation (1.1) can also be derived if the strain matrix $[\bar{\varepsilon}]$ is measured:

$$[F]=[\bar{\varepsilon}][C] \tag{1.2}$$

This formula expresses the linear relationship between the external load matrix $[F]$, the measured strain matrix $[\bar{\varepsilon}]$ and the correlation matrix $[C]$ based on the finite element calculation. According to the linear relationship between the strain and the external load, in order to solve for [C] in equation (1.2), the loads [F] can be assumed to be unit loads. This then allows the term [F] in equation (1.2) to be replaced with the identity matrix [I] as shown in equation (1.3).

$$[\varepsilon][C]=[I] \tag{1.3}$$

This then allows for the [C] matrix to be solved via equation (1.4). Recall from linear algebra that equation (1.4) is the matrix representation of least squares fit.

$$[C]=[\varepsilon^T \varepsilon]^{-1} \varepsilon^T \tag{1.4}$$

The most stable [C] matrix can be found by choosing strain gauge locations that make the determinant of $[\varepsilon^T \varepsilon]$ maximum (equation (1.5)). The D-Optimal search approach is used to find the gauges that satisfy equation (1.5). The gauges that satisfy equation (1.5) are the optimal strain gauge placements to be sensitive to all of the applied unit load cases.

$$\left|\varepsilon^T \varepsilon\right| \rightarrow \max \tag{1.5}$$

The steps used in the True-Load software implementation of the load back calculation process is:

1. Establish the finite element model of the structure. Apply unit loads on the structure and store strain results.
2. For the True-Load algorithm, select a set of elements in nominal areas of the FEA model to be used for the D-Optimal gauge search. Specify the desire number of gauges to be located.
3. The gauges will be located such that equation (1.5) is satisfied.
4. Install the gauges on the test object and collect time histories of strain data in response to the applied test loads.
5. The True-Load software will multiply the measured strains from step (4) by the correlation matrix found in step (3). This multiplication will produce the loads from the measured strain.

2 Wheel load reverse test

The load calculation algorithm of software True-Load will be tested using, the wheel as the subject in this research. The wheel was tested with known loads and the True-Load algorithm was used to calculate the applied loads to further the understanding of the algorithm. The loads calculated from True-Load will be compared to the loads in applied in test environment.

2.1 Establish wheel set finite element model

The FEA model was created from as STEP file. The axle and wheel were meshed with 2^{nd} order tetrahedron elements (C3D10). The assembly of the FEA components consisted of the axle and two instances of the wheel. The faces of the axle and the wheel were surface coated with membrane elements (M3D6).The True-Load software uses 2D elements (membranes, shells) for placement of strain gauges. Membrane elements also provide more accurate surface strains from solid elements without increasing the global stiffness matrix size. Figure 2.1 shows the FEA mesh. The white elements are the membrane elements used for candidate gauge locations.

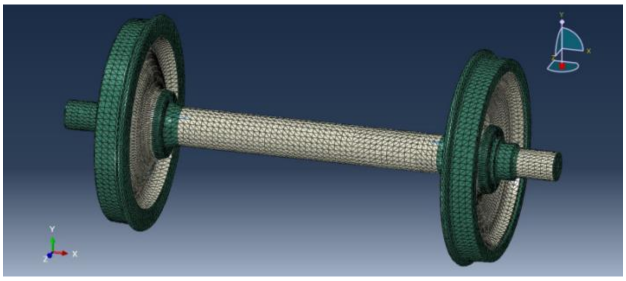

Fig. 2.1 finite element model of the wheel set

2.2 Forward load and its working conditions

This study takes a different F_x, F_y and F_z Combined into three kinds of conditions, as shown in table 2.1, each test will be loaded at different times in different load, which F_x, F_y and F_z respectively shown in figure 2.2.

Table 2.1 Description of test conditions

case	axle						wheel			对应组数
	F_y 10KN			F_z 10KN			F_x 10KN			
	L	R	B	L	R	B	L	R	B	
1	×	×					×	×		一
2			×			×			×	二
3	×	×		×	×		×	×		三
note：L=Left；R=Right；B=Both。 ×表示在此方向加载。										

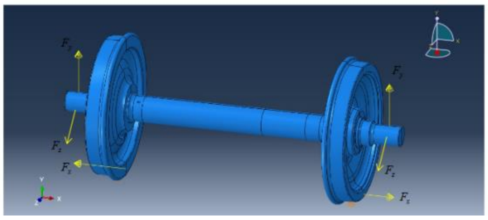

Fig. 2.2 Schematic diagram of the loading position of the finite element model

2.3 Arrangement of strain gauge group

This test select eight strain gauges, its position as shown in Figure 2.3 below.

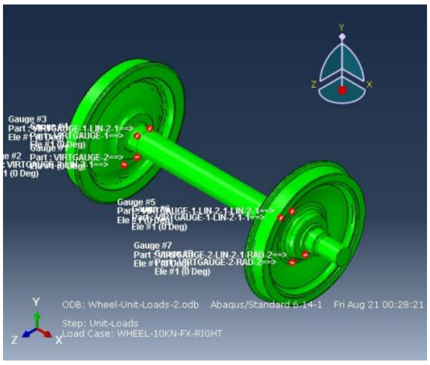

Fig. 2.3 Layout of strain gauge group

2.4 Reverse load data and the comparison

The wheel set was tested on a full scale testing rig as shown in Figure 2.4.

Fig. 2.4 Full Scale Testing Rig

The experimental results show that errors between the calculated load and the actual load range from 1% to 14%. It was found that the finite element model of the wheel does not match the real geometry of the wheel These geometric differences caused differences in stiffness and the corresponding strain response. It is believed that this geometric difference is the largest source for error. Other errors could be the physical placement of the strain gauges on the wheel. However, the error in gauge placement is believed to be negligible. The following table shows the contrast between load back calculation and the real load:

Table 2.2 comparison of the first set

Load unit: KN

t/s		axle		wheel	
		Y Left	Y Right	X Left	X Right
1	Calculated	-2.56	-2.94	-0.13	-0.35
	Applied	-2.97	-3.00	0.00	0.00
	Error	14%	2%	——	——
5	Calculated	-5.71	-6.36	-0.31	-0.70
	Applied	-6.60	-6.70	0.00	0.00
	Error	14%	5%	——	——
9	Calculated	-5.11	-5.98	2.29	2.40
	Applied	-5.40	-5.40	2.32	2.32
	Error	5%	-11%	1%	-3%
Note：Error=（Applied-Calculated）/Applied。					

Table 2.3 comparison of the second set

Load unit: KN

		Axle				wheel	
t / s		Y Left	Y Right	Z Left	Z Right	X Left	X Right
1	Calculated	-2.77	-2.77	-0.01	-0.01	-0.24	-0.24
	Applied	-2.97	-3.0	0.00	0.00	0.00	0.00
	Error	7%	8%	——	——	——	——
5	Calculated	-6.07	-6.07	0.05	0.05	-0.51	-0.51
	Applied	-6.60	-6.7	0.00	0.00	0.00	0.00
	Error	9%	9%	——	——	——	——
9	Calculated	-5.56	-5.56	0.07	0.07	2.34	2.34
	Applied	-5.40	-5.4	0.00	0.00	2.32	2.32
	Error	-3%	-3%	——	——	1%	
Note：Error=（Applied-Calculated）/Applied。							

Table 2.4 comparison of the third set

Load unit: KN

		Axle				wheel	
t / s		Y Left	Y Right	Z Left	Z Right	X Left	X Right
1	Calculated	-2.56	-2.94	-0.08	0.07	-0.13	-0.35
	Applied	-2.97	-3.00	0.00	0.00	0.00	0.00
	Error	14%	2%	——	——	——	——
5	Calculated	-5.71	-6.36	-0.23	0.35	-0.31	-0.70
	Applied	-6.60	-6.70	0.00	0.00	0.00	0.00
	Error	14%	5%	——	——	——	——
9	Calculated	-5.11	-5.98	0.03	0.11	2.29	2.40
	Applied	-5.40	-5.40	0.00	0.00	2.32	2.32
	Error	5%	-11%	——	——	1%	-3%
Note：Error=（Applied-Calculated）/Applied。							

From the above table, we can see that the error between the calculated load and the real load can have errors as high as 14%. It is believed that the geometric differences between the FEA model and the test part are the largest source for this error. As can also be seen in the above tables, most of the error is below 5% for the loads

3 Discussion on algorithm Scientifically

In this study, we find that the proposed algorithm is used to find out the optimal location of the strain gauge in the initial strain gauge group by using the D-Optimal optimization algorithm. The optimum set of gauges is influenced primarily by the user’s selection of candidate elements used in the search. These elements must be in nominal, low strain gradient areas. The selection of these areas are subject to user discretion. Once the optimal gauges are found, user edits are performed in order to make the gauges easier to place in the lab. While, theoretically there is one set of optimal gauges to be used, there is a very large set of suitable gauges that may be used for efficient gauge placement in the laboratory environment. When the object is relatively simple (e.g. a cantilever beam), the user may rely in engineering judgement for gauge placement. However for complex structures, an automated D-Optimal method of gauge placement similar to that provide by True-Load is needed to have meaningful strain measurements that support load back calculation. True-Load has shown value in supporting reliable load back calculation.

4 Summary

This paper takes the wheel set as a subject that was used for research on reverse evaluation of the load based on True-Load algorithm. Although the problem studied is a relatively simple problem, but the results seems to indicate that the necessary conditions for the success of this approach are: (1) the finite element model (FEM) must be reasonable representation of the structural stiffness and nominal strain; (2) the optimal location of the strain gauge must be included in the selected locations of strain gauges.

For these conditions above, the first can be achieved reasonably well as long as there is proper 3D CAD data available that represents the test article. For the second condition, experience with application of the strain gauges and choices for unit-load cases is critical to the success.

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