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*Abstract*

# Nondestructive inspection of bonded components by singular value decomposition of time-series temperature variation data †

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## 1. Introduction

In order to improve fuel economy, automobiles are required to be lighter. While using high-strength steel plates can reduce a vehicle's weight, using thinner steel plates reduces its rigidity. Recently, a steel joining method called weld bonding has attracted attention for improving body rigidity. This method combines spot welding and adhesive to join steel plates together, compensating for the reduction in rigidity caused by the plates being thinned down. Since the stiffness-enhancing effect of this method depends on the adhesive areas being filled, these areas are an important inspection item. Conventional sampling inspection can only evaluate the cut surfaces and cut parts cannot be used; therefore, a method that enables non-destructive inspection is required. Rajic et al. [1] proposed principal component thermography (PCT), which uses singular value decomposition (SVD) on data obtained by active infrared thermography with flash lamp heating. They demonstrated that PCT provides high levels of thermal contrast for underlying structural flaws in composite materials. In this study, we focused on an analysis method using SVD to inspect bonding areas. Pulse heating with a flash lamp is applied to a weld-bonded specimen and SVD is applied to the time-series temperature variation data to improve the accuracy of inspecting bonding areas.

## 2. Principle of SVD analysis

The principle of SVD analysis is explained below. Infrared image data $\varphi$ obtained by infrared thermography is a three-dimensional image matrix containing $n_t$ frames of $n_x \times n_y$ infrared images. To perform SVD, the matrix $A_k$ consisting of the $n_x \times n_y$ pixels of the kth frame shown in Equation (1) is reordered into the column vector $x_k$ shown in Equation (2).

$$A_k = \begin{pmatrix} a_{11} & \cdots & a_{1n_y} \\ \vdots & \ddots & \vdots \\ a_{n_x1} & \cdots & a_{n_xn_y} \end{pmatrix} \; k = 1,2,\dots,n_t \tag{1}$$

$$x_k = \begin{pmatrix} a_{11} \\ \vdots \\ a_{1n_y} \\ \vdots \\ a_{n_x1} \\ \vdots \\ a_{n_xn_y} \end{pmatrix} \; k = 1,2,\dots,n_t \tag{2}$$

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The column vectors of all frames are arranged as in equation (3) to form a matrix X. Singular value decomposition is then performed to obtain equation (4).

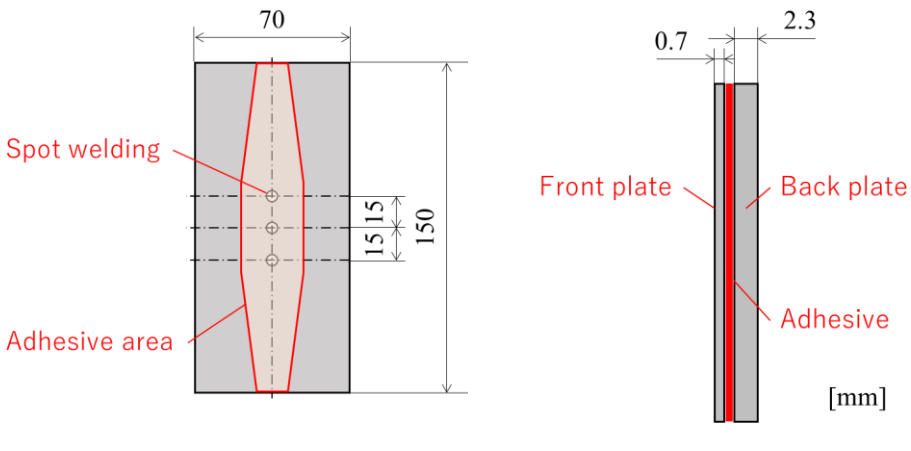
$$X = (x_1, x_2, \dots, x_{n_t}) \tag{3}$$

$$X = U\Sigma V^T = [u_1\ u_2\ \cdots\ u_M] \begin{bmatrix} \sigma_1 & & 0 \\ & \ddots & \\ 0 & & \sigma_M \end{bmatrix} \begin{bmatrix} v_1^T \\ v_2^T \\ \vdots \\ v_M^T \end{bmatrix} = u_1\sigma_1 v_1^T + u_2\sigma_2 v_2^T + \cdots + u_M\sigma_M v_M^T \tag{4}$$

Each column $u_k$ of matrix $U$ is called Empirical Orthogonal Function (EOF), and each row $v_i^T$ of matrix $V^T$ is called PC. EOF is the intensity distribution per pixel for the corresponding PC waveform. In this study, SVD was applied to time-series temperature variation data to enhance the contrast between adhesive-applied and non-applied areas and to improve the accuracy of inspecting adhesive-applied areas.

## 3. Experimental method

In this study, a plate-joined specimen consisting of 0.7 mm and 2.3 mm thick automotive hot-dip galvanized steel sheets joined by adhesive and spot welding was used, as shown in Figure 1. Three spot welds were applied, one at the center of the specimen and the others at a position 15 mm from the center of the specimen. The specimen was coated with flat black paint to improve emissivity. The employed infrared camera was a FLIR SC7500 with InSb MW infrared sensor. Xenon flashlamps were used as heating source. The infrared camera and the flashlamp were placed on the same side of the specimen. The specimen was heated by pulsed heating of the infrared measurement surface and the time-series temperature fluctuations were captured by the infrared camera. Further SVD was applied to the obtained data.




(**a**) (**b**)

**Figure 1.** Plate-joined test specimen employed in this study: (a) Illustration of the specimen of the side for infrared temperature measurement; (**b**) Illustration of cross-section of Figure 1(a).

## 4. Results

Figure 2 shows an infrared image taken at 0.5 seconds after pulse heating. It is found that the spot weld and its surrounding area are cooler than other area of specimen. This is because heat is transferred from the spot welds and the areas of adhesive to the back plate. The adhesive can be detected due to the localized low temperature area. Figure 3 shows the results of applying SVD to time-series temperature variation data. The boundary between adhesive-applied and non-applied areas is clearer in the EOF image than in the infrared image. This indicates that applying SVD improves the accuracy of adhesive inspection.

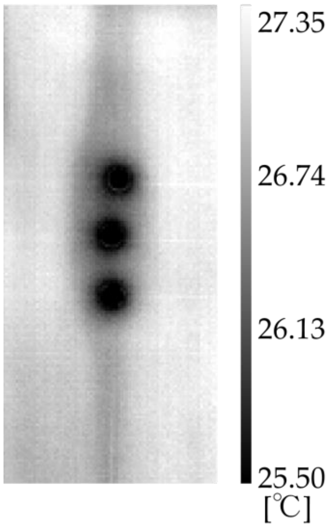



**Figure 2.** Infrared image at 0.5 seconds after pulse heating

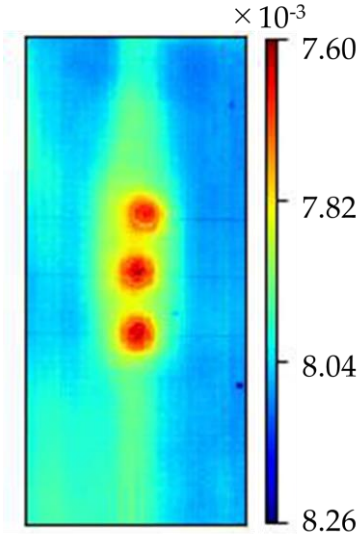



**Figure 3.** Results of the SVD analysis

## 5. Conclusion

For the purpose of inspecting adhesive areas of a weld-bonded specimen, SVD was applied to time-series temperature variation data obtained by active infrared thermography. In this method, the specimen was heated using flash lamp pulse heating. It was found that the boundary of the adhesive areas was successfully enhanced by SVD, improving the accuracy of inspecting adhesive-applied areas.

## References

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