PSEUDO-CRACKING APPROACH TO FATIGUE LIFE ASSESSMENT OF EXISTING RC BRIDGE DECKS BASED ON CRACK INSPECTION DATA

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ABSTRACT

Existing bridge decks in service are undergoing fatigue damage from moving vehicles and cracks often occur at the bottom. Due to the lack of load record, it's difficult to quantitatively assess residual fatigue life of bridge decks. This paper presents pseudo-cracking approach to fatigue life assessment of existing RC bridge decks based on site crack inspection.

By means of pseudo-cracking, firstly conversion of observed cracks' data into space-averaged strain field is conducted followed by numerically reproducing an equivalent damage states in the finite element scheme. Then, sensitivity analyses are conducted to compute the S-N diagram of the damaged decks subjected to different moving vehicles loads by applying the residual life numerical scheme. To the end, by taking into account the real traffic volume of bridges in future, we can predict the residual life of existing bridge decks. Proper maintenance measures can be recommended to assure the safety of existing bridge decks as well.

Keywords: RC bridge deck, pseudo cracking, residual fatigue life, S-N diagram, FEM analysis.

1. INTRODUCTION

Reinforced concrete bridge decks are directly exposed to repeated traffic loads. According to survey, many in-service bridges designed by old codes suddenly ended with collapsing of concrete decks (Ji *et al.* 2010). Herein, engineers are often concerned with deck degradations such as cracks on the bottom and deflections of decks. Many studies found that degradation of concrete decks is caused by high cyclic loading of heavy traffics, temperature changes, ASR and corrosion of reinforcement. Among these causes, cyclic load effect is a primary issue for practice.

In order to maintain the bridge decks, the importance is to assess their residual service life. Since 1970s, many research efforts have been made on the fatigue life assessment of the reinforced concrete decks under moving load (CEB, 1988, Holmen, 1975, Matsui 1987, Schläfli *et al.* 1998, Oh *et al.* 2007, Yoshitake *et al.* 2010). Such fruitful results might lead to a reliable design method

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for the decks without any initial damage. However, the loading history is usually needed for the safety assessment of existing bridge decks which are suffering greatly from the traffic vehicles; yet the questions could remain with the lack of detailed records. It is certain that the residual life assessment method and maintenance strategy are required for damaged decks.

Recently, fatigue life assessment scheme of reinforced concrete structures with nonlinear finite element methods has been further developed by the authors (Maekawa *et al.* 2006). Nonlinear fatigue constitutive models of concrete in tension, compression and shear along crack planes were proposed. The microscopic material states at each moment and location on the loading path can be traced in the finite element analysis. On this framework, the mechanical damage and plasticity of concrete under high repetition of loads can be fully traced by a logarithmic direct-path integration (Maekawa *et al.* 2008). This computational scheme has been further enhanced for the simulation of bridge deck performance under high cycle moving loads (Fujiyama and Maekawa 2011). Employing this to practical life assessment of existing structural concrete, a methodology has been proposed with reasonable simplification, called pseudo-cracking method (Fujiyama *et al.* 2013).

In this paper, the authors try to predict the residual life of two existing bridge decks by means of pseudo-cracking and specific analysis system for slabs in real service. Meanwhile, the real vehicles volume of each bridge slabs was taken into account, residual life of the two bridge decks was calculated quantitatively and proper remedial measures were recommended. Finally, the authors introduce FABriS system, which is specifically to deal with life estimation on site of maintenance.

2. METHODOLOGY

2.1. Pseudo-cracking approach

Conventional assessment methods usually require the loading history of the moving vehicles, but generally, detailed records are not available. Herein, the authors proposed the pseudo-cracking scheme based on observed cracking damage for the in-service decks (Fujiyama *et al.* 2013), which can reproduce the cumulative crack damage of a deck and estimate its residual life. **Figure 1** shows the flowchart of the pseudo-cracking method. Six steps should be followed:

First, site crack inspection of a deck should collect the width and location of cracks at the bottom of deck. Second, preparation for finite elements model for deck is conducted. Conversion of crack widths and location to the equivalent stain field is made in each layer by,

$$\varepsilon_{x0}^{1} = \frac{\sum_{i=1}^{n} \omega_i \cos\theta_1}{l_x}, \varepsilon_{y0}^{1} = \frac{\sum_{i=1}^{n} \omega_i \cos\theta_2}{l_y} \tag{1}$$

Third, conversion of the equivalent average strain into “input strain” is required according to following formulations:

$$\varepsilon_{x1}^{1} = \alpha\varepsilon_{x0}^{1}, \varepsilon_{y0}^{1} = \alpha\varepsilon_{y0}^{1}; (\varepsilon_{x0}^{1}, \varepsilon_{y0}^{1} < \beta)$$
$$\varepsilon_{x1}^{1} \cong \varepsilon_{x0}^{1}, \varepsilon_{y0}^{1} \cong \varepsilon_{y0}^{1}; (\varepsilon_{x0}^{1}, \varepsilon_{y0}^{1} \geq \beta) \tag{2}$$

The fourth step is to restrain all nodal displacements and to calculate the inner stress caused by the converted input strain. The fifth is to remove restraints for complete equilibrium amongst nodal forces, and the path-dependent internal variables are taken over in the step 4. After employing the built-in of pseudo-cracking, the damage state of the bridge deck is introduced into numerical analysis (Fujiyama, *et al.* 2013).

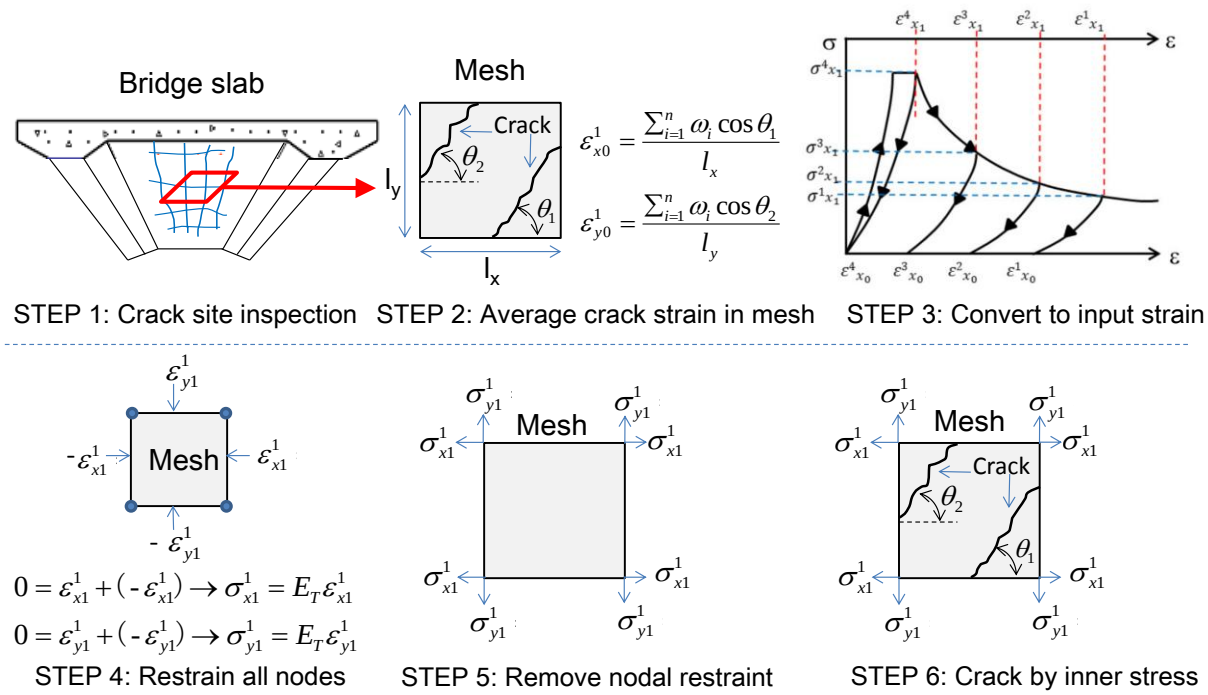


Figure 1 Concept and flow of pseudo-cracking approach

2.2. Scheme of numerical analysis for high cycle moving load

After reproducing the damage state equivalent to the slab in reality, the constitutive laws of concrete are used for the subsequent fatigue analysis by the path-dependent integral scheme (Maekawa *et al.* 2003). For the high cycle fatigue problems, those basic models are enhanced to consider the cumulative fatigue-time damaging. The direct path-integral scheme for high cycle fatigue load (Maekawa *et al.* 2006) is shown in **Figure 2**. The cumulative fatigue-time damage is considered as time-dependent plasticity and fracturing in this scheme.

3. ANALYTICAL STUDY

For application, two existing bridge decks (O Bridge in Nagano 1963, S Bridge in Tochigi 1979) in Japan are investigated in line with the pseudo-cracking. Both bridges were built more than 30 years before. Due to fatigue damage by road vehicles, many cracks were found at the bottom of the decks. Both bridges are in service of the national road with heavy traffics. Maintenance and strengthening

of their bridge decks are thought to be necessary for safety assurance. Herein, the residual life assessment was of great importance. The detailed dimensioning of the bridge deck structures and FEM models can be referred as shown in **Figure 3**.

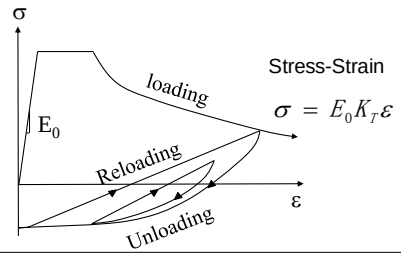
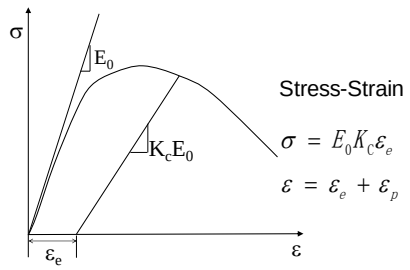
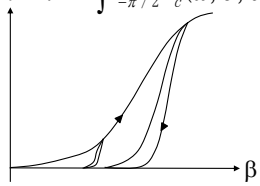
	Constitutive models of concrete	**Enhanced models for high cycle fatigue**
Tension model		K_T is the tensile fracture parameter, which stands for path-dependent instantaneous fracturing, cumulative fatigue damage and time-dependent tension creep. $dK_T = Fdt + \boxed{G}d\varepsilon + Hd\varepsilon$ Cyclic fatigue damage (Maekawa *et al.* 2006)
Compression model		K_C is the compression fracture parameter. The nonlinearity of concrete is represented by *it*. The time dependent plasticity, fracturing and cyclic fatigue damage are taken into account in parameter K_C. $dK_C = \left(\frac{\partial K_C}{\partial t}\right)dt + \boxed{\left(\frac{\partial K_C}{\partial \varepsilon_e}\right)}d\varepsilon_e$ Cyclic fatigue damage $d\varepsilon_p = \left(\frac{\partial \varepsilon_p}{\partial t}\right)dt + \left(\frac{\partial \varepsilon_p}{\partial \varepsilon_e}\right)d\varepsilon_e$ (Maekawa and El-Kachif *et al.* 2004)
Crack shear model	$\tau = \int_{-\pi/2}^{\pi/2} R_c'(\omega, \delta, \theta) \sin\theta d\theta$ 	τ_0 is the original shear stress of concrete, and represents the slip and width of crack, and X is the accumulated path function, which indicates the cyclic damage for shear transfer. (Maekawa *et al.*, *2006*) $\tau = \boxed{X} \cdot \tau_0(\delta, \omega)$ $X = 1 - \frac{1}{10}\log_{10}\left\{1 + \int \left\|d(\delta/\omega)\right\|\right\} \geq 0.1$

Figure 2 Time path-dependent constitutive fatigue models of concrete (Maekawa *et al*. 2006)

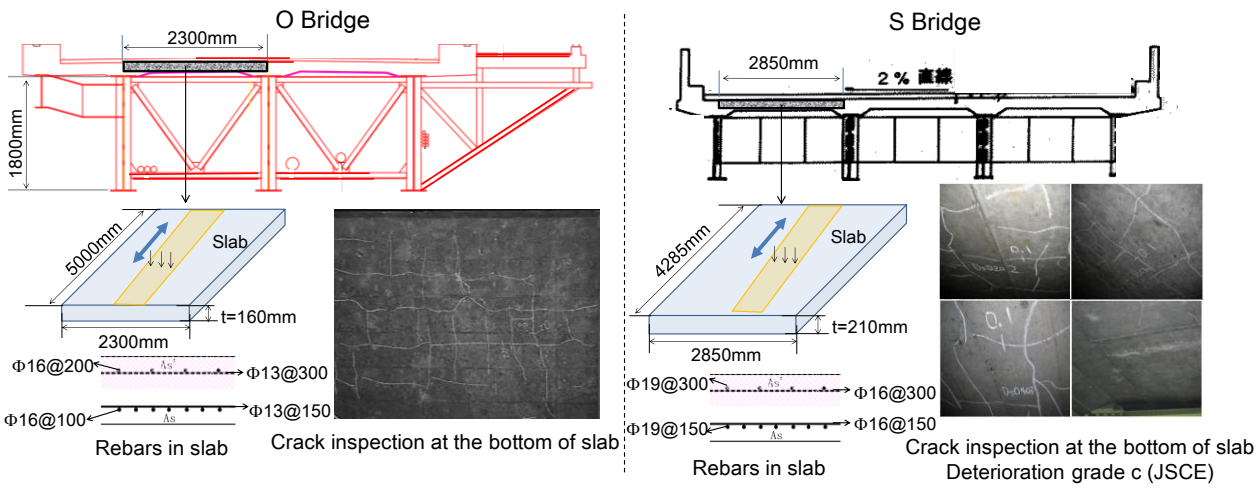


Figure 3 Two existing bridge decks and crack inspection for analysis

3.1. Crack inspection and analytical cases

For O bridge, the crack image from site inspection (**Figure 3**) corresponds to the average crack width of about 0.2mm. For S Bridge, engineers judged the crack deterioration grade "c" according to the standard. The boundary conditions are taken into account so that the slab is supported by longitudinal girders alone. **Table 1** shows cases of two bridges and material properties of both concrete and reinforcing bars.

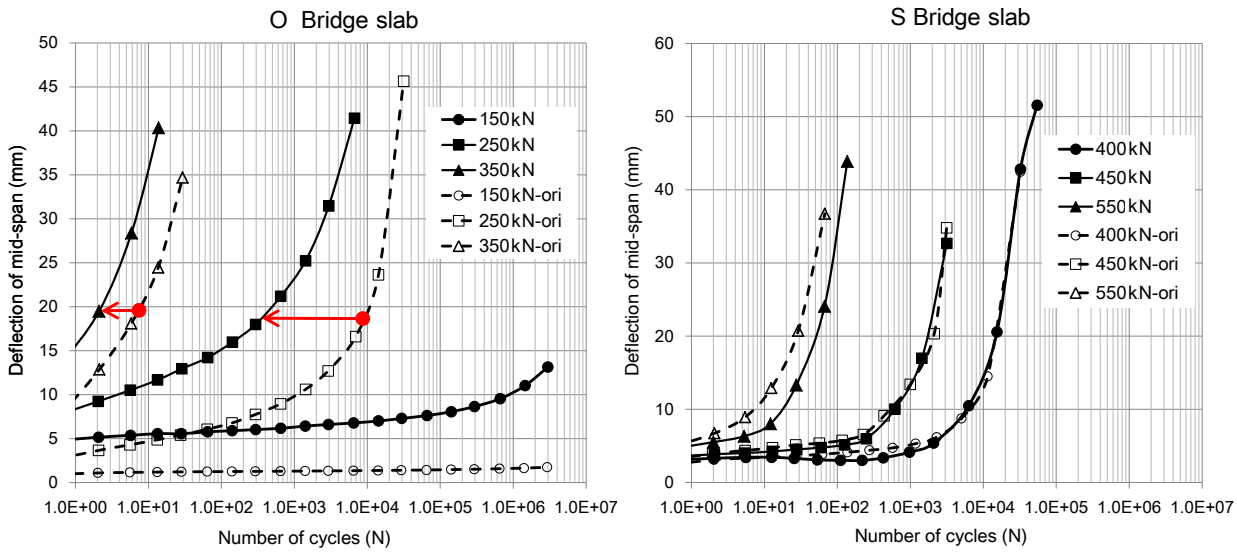
Table 1: Cases and material properties

	Case	*Crack damage*	f_c *(MPa)*	f_y *(MPa)*
O Bridge	I	Measured Crack	24	295 (SD295)
	II	Without		
S Bridge	I	Crack grade	35	295 (SD295)
	II	Without		

3.2. Simulation results

Then pseudo-cracking and RC fatigue analysis scheme were applied to analyze the residual life of bridge decks. After pseudo-cracking procedure, the initial crack damage was rebuilt in the numerical analysis. Different levels of traffic loads in future were applied on the bridge decks with damages equivalent to the current states.

Figure 4 shows the mid-span deflection of bridges decks under different traffic loads. For O Bridge built in 1963, when taking the real crack state into account, the possible number of cycles is reduced to about 1/10 of the sound one. For S bridge built in 1979, the crack damage grade was regarded as "c" as stated above, but the computed remaining life is not so much different.



(a) O Bridge deck: mid-span deflection (b) S Bridge deck: mid-span deflection

Figure 4 Comparison of mid-span deflection of deck with/without crack damage

As for a further discussion, 1/200 of the deck span was taken as the failure criterion in terms of the center deflection. **Figure 5** shows the S-N diagrams of the four cases.

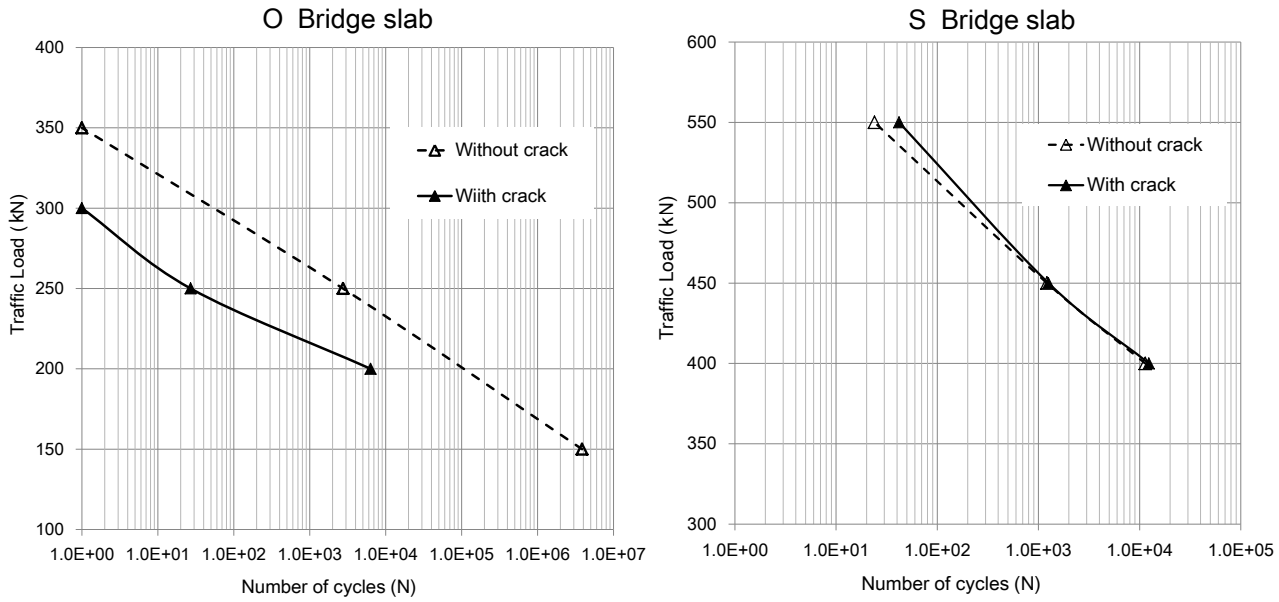


Figure 5 S-N diagrams of the two decks (S: Traffic Load)

3.3. Residual life prediction according to measured traffic volume

Both bridges were designed under the standard wheel-type load as TL-20 (wheel load is 100kN). The wheel impact factor was estimated about 0.27. So, the design wheel load was calculated as: S=100 *(1+0.27) =127kN. The measured averaged traffic volume V for O and S Bridges are about 2,475 and 34,200 day/line/direction. According to equation (3) and equation (4) for the deck fatigue life assessment in a dry condition (Matsui 2007), number of cycles can be estimated by,

$$p_{sx} = 2B(f_v x_m + f_t C_m) \tag{3}$$

$$\log(p / p_{sx}) = -0.07835 \log N + \log 1.52 \tag{4}$$

Meanwhile, S-N relation can be obtained by the linear regression analysis from **Figure 5**. The residual life can be calculated from S-N relation and the measured traffic volume, where S is the traffic load (kN) and N is the number of cycles.

For O Bridge deck, empirical formula says $\Delta T_c = N/V/365 \approx 23.4$ years;

with crack: $\log N = -0.038S + 11.25, R^2 = 0.9801$ (5)

$N = 10^{-0.038 \times S + 11.25} = 2654605$ cycles, Residual life $\Delta T_c = N/V/365 \approx 2.94$ years;

without crack: $\log N = -0.0329S + 11.573, R^2 = 0.9994$ (6)

$N = 10^{-0.0329 \times S + 11.573} = 24814184$ cycles, Residual life $\Delta T_0 = N/V/365 \approx 27.5$ years.

For S Bridge, the given empirical formula is $\Delta T_c = N/V/365 \approx 47.8$ years;

with crack: $\log N = -0.00162S + 10.506, R^2 = 0.994$ (7)

$N = 10^{-0.0162 \times S + 10.506} = 280931216$ cycles, Residual life $\Delta T_c = N/V/365 \approx 22.5$ years;

without crack: $\log N = -0.0163S + 10.514, R^2 = 0.9956$ (8)

$$N = 10^{-0.0177\times S+11.113} = 732993291 \text{ cycles, Residual life } \Delta T_0 = N/V/365 \approx 58.7 \text{ years.}$$

Comparing with the fatigue life of cracked and the sound deck, **Figure 6** indicates that O Bridge suffered from much severer deterioration, and appropriate repair or maintaining measures should be taken. For S Bridge, quantitative intensity investigation is highly recommended as well.

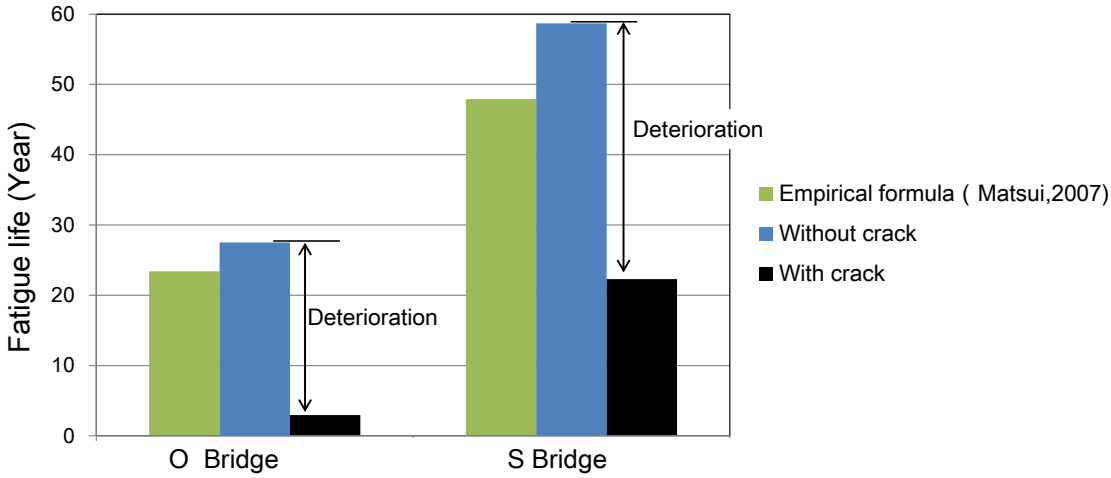


Figure 6 Compare residual life of decks

3.4. FABriS for practical application based on pseudo-cracking approach

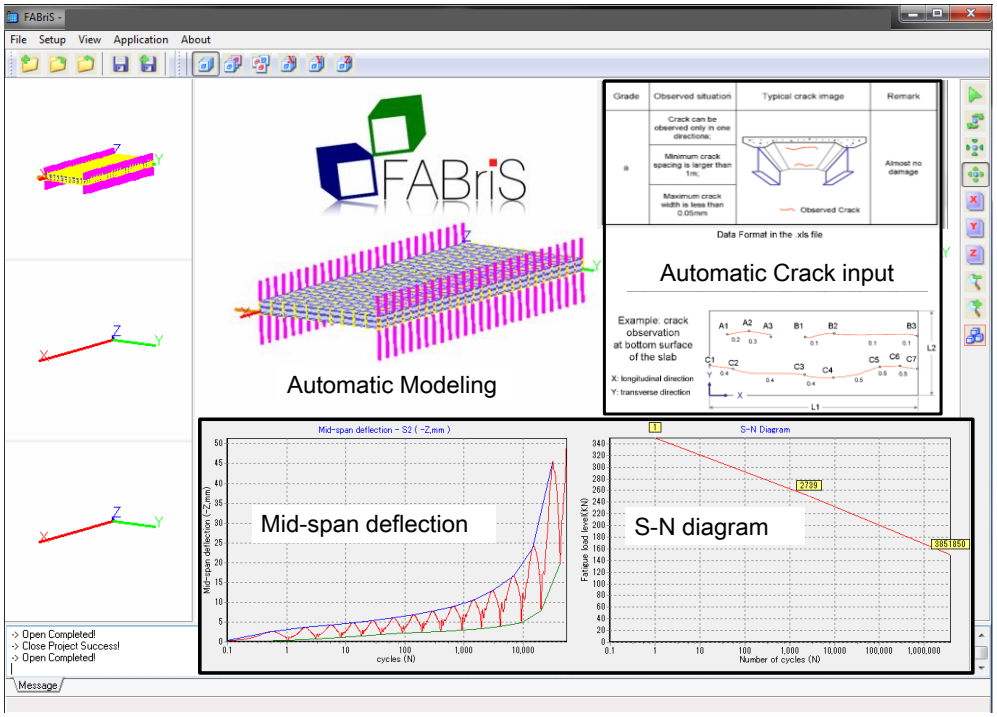


Figure 7 FABriS system based on pseudo-cracking approach

For a practical application of users' friendly, the authors introduced a FABriS (**F**atigue **A**nalysis for **B**ridge **Deck**) system, which enables us to combines the pseudo-cracking and the practical simplification. FABriS system is designed to deal with the three-dimensional nonlinear FE analysis of existing reinforced concrete bridge deck structures to estimate residual fatigue life. As shown in **Figure 7**, FABriS can help engineers to complete the 3D FEM model of deck and convert crack inspection data automatically, and also automatically export S-N diagrams and mid-span deflection directly.

4. CONCLUSIONS

The residual fatigue life of existing bridge decks was experimentally and numerically studied by calling for the pseudo-cracking approach. Based on the site crack inspection and the measured traffic volume of each bridge, the authors try to evaluate fatigue life of decks. Due to reasonable simplification and the quantitatively estimating, this approach could help engineers to evaluate the deterioration state of ridge decks in service and help to decide the remedial measure for decks. Future studies may focus on more experimental verification and analytical investigation.

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