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Performance evaluation of lattice girder and significance of quality control

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ABSTRACT

It has been reported that lattice girders fail due to inadequate steel members. An experimental analysis is herein conducted using material and structural tests to determine the behavior of lattice girders made of B500B and SS400, two representative steel materials. A numerical analysis is also carried out to evaluate the performance of lattice girder in a tunnel. Both the experimental and numerical study indicated that the use of inadequate steel members results in a significant reduction in the working load and can also affect the overall structural stability of the tunnel. Therefore, quality control for lattice girders is of great importance. A review of the quality control systems for lattice girders reveals it to be desirable to introduce an on-site testing method to identify the adequacy of a steel member in the field. Thus, the portable indentation test is suggested as an on-site quality control test for a lattice girder.

1. Introduction

A lattice girder is an important primary tunnel support for NATM, and it has become increasingly popular due to its simple installation process and structural benefits. The lattice girder was introduced to overcome the weakness of H-shaped steel ribs, and its geometric characteristics significantly reduce the possibility of an internal gap (Braun, 1983, Baumann and Betzle, 1984; Komselis et al., 2012). The flexural stiffness and strength of lattice girders have been studied via analytical and experimental methods, and its structural benefits were widely recognized (Baumann and Betzle, 1984; Haack, 1989; Yoo et al., 1997; Kim and Bae, 2008; Galler et al., 2009).

Nevertheless, local failures or fractures have been reported for lattice girders (Kim et al., 2013; KTA, 2016), and Fig. 1 presents cases demonstrating such failures. Both overall and local failures have been reported for lattice girders, and the failure can be a result of various conditions, such as not being fully combined with shotcrete, insufficient shotcrete thickness, uneven stress acting on the lattice girder, and so on.

One specific reason that has been recently recognized is the use of inadequate steel members for the lattice girder. When the yield strength of the steel member constituting the lattice girder is not sufficient to resist ground loading, the lattice girder becomes susceptible to failure and can threaten the overall stability of the tunnel. Thus, the yield strength of steel members constituting the lattice girder needs to be evaluated. However, the structural contribution of the lattice girder on the lining performance of tunnels is not generally considered quantitatively and is frequently ignored during design.

This study investigated the performance of lattice girders by mainly focusing on the type of steel material. Two representative types of steel members are considered since the number of types of steel materials that are mainly used to manufacture lattice girders is limited. B500B satisfies international standards, and SS400 does not satisfy the standards but is often used in the field instead of B500B.

Particular cases of failure have also indicated that on-site quality control is required to prevent the use of inadequate steel members. In general, quality control for lattice girders has been carried out using a mill sheet during manufacturing. However, the quality of the steel member is not tested at the construction site immediately before installation. Developing a method to do so would be significant since a steel member cannot be easily identified in the field, and no testing methods are currently available at the construction site.

2. Characterization of the mechanical behavior

2.1. Steel materials and lattice girder

According to international standards of tunnel design, the yield strength of the steel material for a lattice girder should be greater than

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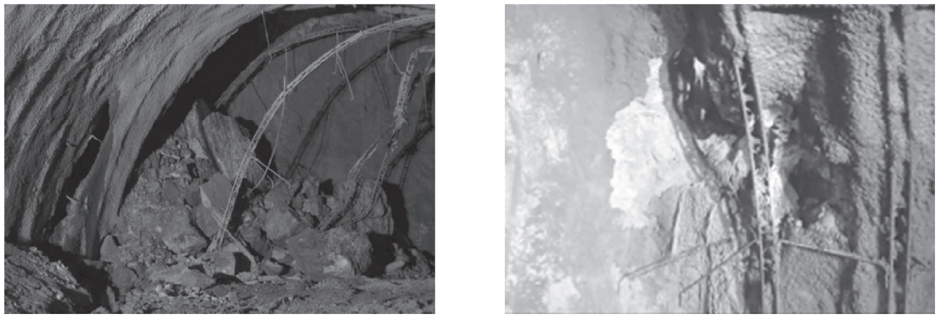

(a) dislocation due to overall collapse (b) local distortion

Fig. 1. Failure cases of lattice girder.

Table 1
Strength criteria for a lattice girder (BS 4449, 2005).

Category	Bar	Spider
Yield strength	≥ 520 MPa	≥ 500 MPa
Tensile strength	≥ Tensile strength × 1.15	≥ 550 MPa

500–520 MPa, and it should be easily welded to connect the parallel steel members (Baumann and Betzle, 1984; BS 4449, 2005; DIN 488-1, 2009; DIN 488-5, 2009). Table 1 shows the strength criteria of the steel members for a lattice girder.

The significance of the minimum yield strength as well as the effect of quality assurance have not been sufficiently examined. In this study, the significance of the steel material constituting the lattice girder is investigated by considering two representative types of steel materials: B500B and SS400. B500B steel is highly ductile and is used as a standard material for reinforcement in many European countries. Meanwhile, SS400 structural steel is available as hot-rolled sheets, flats and bars and is commonly used instead of B500B, particularly in Asia. SS400 is less expensive and is easier to weld and machine, but it has relatively low strength and doesn't satisfy the strength requirements for lattice girders. The mechanical properties for B500B and SS400 are listed in Table 2.

In this study, three types of lattice girder were considered according to the size and types of steel of the lattice girder. These are denoted as H-50, H-70 and H-95, where H is the distance from the upper bar to the lower bar. Table 3 presents the geometries and properties of the lattice girders considered in this study.

2.2. Material behavior: Uniaxial tensile test

The fundamental behavior of the two steel materials is investigated using a tensile strength test. The tensile strength test is conducted according to ASTM E8/E8M-15a. In total, 12 samples were chosen considering the type of lattice girder (H-50, H-70 and H-95) and parts (upper and lower). Fig. 2 shows the typical stress-displacement curve

Table 2
Two representative steel materials used for lattice girders (BS 4449, 2005; EN 1992-1-1, 2004; KS D3503, 2014).

Steel material	Density (kg/m^3)	Elastic modulus (GPa)	Average tensile strength (MPa)	Average yield strength (MPa)	Poisson's ratio
B500B	7860	231.4	643	546	0.26
SS400	7860	205.0	448	315	0.26

Note: The strength characteristics of B500B refer to BS 4449 (British Standard). The strength characteristics of SS400 refer to KS D3503 (Korean Industrial Standards).

obtained from the tensile strength test. Fig. 3 shows the samples after the test.

SS400 is more ductile than B500B, and the yield and tensile strength of SS400 are significantly lower than those of B500B by about 42–43% and 29–31%, respectively. As shown in Fig. 4, these do not satisfy the yield strength criteria for a lattice girder.

2.3. Structural behavior: 4-point bending test

The structural behavior of the lattice girder is investigated using the 4-point bending test that was developed to evaluate the structural performance of a bending member (Kim and Bae, 2008). The test can provide an important, useful index as the basis for a quantitative estimation of the structural performance of the moment-resisting member. The test is also useful to examine the possibility of local failure at the welding joints.

The 4-point bending test performed in this study is presented in Fig. 5. There are two supports and two loading points in the 4-point bending test. The distance between the two supports is 1.5 m, and the distance between the two loading points is 0.5 m. The specimen is the 2 m long lattice girder segment.

In total six different types of lattice girders were tested in this study according to the size of the lattice girder and the type of steel material used. To avoid biased results, three samples were tested for each case, and the results were averaged.

The maximum loads measured during the 4-point bending test are presented in Fig. 6. The maximum loads obtained from SS400 members are considerably smaller than those obtained for B500B, and this implies that the yield strength of the steel member can have a significant influence on the structural resistance of the overall lattice girder. Maximum bending load for SS400 was 83–88% that of B500B, i.e., a reduction in the tensile strength of 29–31% results in a decrease in the moment resistance of the lattice girder by 12–17%, as shown in Fig. 7(a). The maximum bending load is also shown to decrease as the H (distance from the center of the upper bar to the center of the lower bar) increases.

The performance of the lattice girder is also evaluated in terms of the displacement at an allowable working load of $P = 0.8 \times P_{max}$. At the center of the sample, the maximum displacement for SS400 is 21–44% larger than that of B500B, as shown in Fig. 7(b).

3. Performance of a lattice girder on the tunnel behavior

3.1. Modeling consideration of the lattice girder

Although the 4-point load test can determine the structural characteristics of the lattice girder, doing so is a considerable simplification of the loading mechanism in an actual tunnel. Thus, the structural contribution of the lattice girder needs to be evaluated within an actual tunnel support system. A finite element analysis was performed to