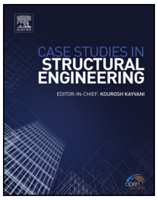
Case Studies in Structural Engineering 6 (2016) 103–114

Contents lists available at ScienceDirect

Case Studies in Structural Engineering

journal homepage: www.elsevier.com/locate/csse



Material strength of long-term used penstock of a hydroelectric power plant

F. Kawamura[a], M. Miura[a], R. Ebara[b], K. Yanase[b,c,*]

[a] Yonden Consultant Inc., Kagawa, Japan
[b] Institute of Materials Science and Technology, Fukuoka University, Fukuoka, Japan
[c] Department of Mechanical Engineering, Fukuoka University, Fukuoka, Japan

ARTICLE INFO

Article history:
Received 25 April 2016
Accepted 6 June 2016
Available online 18 July 2016

Keywords:
Sustainability
Strength
Chemical compositions
Non-destructive evaluation
Carbon steel

ABSTRACT

In this study, the material strength of a carbon steel (JIS SS400), which has been used for the penstock of a hydroelectric power plant for about 50 years, is examined. A series of data were obtained and analyzed by measuring the chemical compositions, observing the macro- and micro-structure and conducting tensile tests. The present study revealed that the material strength (0.2% proof strength and ultimate tensile strength) measured at one site can not be regarded as a reliable representative of the entire structure. On the other hand, strong and positive correlation between equivalent carbon content and material strength indicates that measuring the former is an effective and reasonably accurate estimate of the latter. In addition, potential use of nondestructive evaluations, including the Vickers hardness, and their reliability is discussed. In practice, a series of statistical analysis with those valuable field data provides us with the insight on the material strength of long-term used penstock.

1. Introduction

During the rapid economic growth era after World War II, a number of steel infrastructures (e.g., bridges, towers and pressure vessels) were constructed in Japan. Some of them are still in use, more than 50 years since their construction. However, it is sometimes difficult to check their material properties because of the lack of relevant records, such as mill sheets, blueprints and specification documents. Given the recent engineering practice of life extension for the existent infrastructures, it is very important to develop reliable methodologies for proper evaluation of infrastructure integrity [1]. Correspondingly, a number of studies have been conducted to analyze and quantify the integrity of existent steel structures. Currently, it is common to use the cut-out specimens to perform the tests and characterize the material properties and performance. However, such approach causes temporal malfunction of the operating infrastructure, which raises the testing costs as a result. Further, it is doubtful that a specimen taken from a specific site is a reliable representative of the entire structure. Therefore, development of non-destructive evaluations would facilitate conducting more cost-effective, efficient and reliable analyses.

In this study, the material strength of a carbon steel (JIS SS400), which has been used for the penstock of a hydroelectric power plant for about 50 years, is examined. A series of data were obtained and analyzed by measuring the chemical

---

* Corresponding author at: Institute of Materials Science and Technology, Fukuoka University, Fukuoka, Japan.
E-mail address: kyanase@fukuoka-u.ac.jp (K. Yanase).

http://dx.doi.org/10.1016/j.csse.2016.06.002

Table 1
Summary of penstock.

Total pipe length (m)	Inner diameter (m)	Pipe thickness (mm)	Gross weight (tf)	Completion year
1096	0.7–2.1	8–25	800	1953

Table 2
Chemical compositions at 1/4 of specimen thickness (mass%).

Specimen thickness (mm)	Chemical compositions (mass%)					
	C	Si	Mn	P	S	Ceq
10	0.20	0.01	0.39	0.003	0.022	0.265
	0.18	0.01	0.40	0.003	0.019	0.247
	0.14	0.02	0.45	0.006	0.023	0.216
15	0.17	0.01	0.49	0.003	0.021	0.252
	0.14	0.01	0.43	0.007	0.048	0.212
	0.19	0.01	0.48	0.009	0.049	0.270
20	0.16	0.01	0.42	0.009	0.025	0.230
	0.17	0.01	0.44	0.009	0.049	0.244
	0.13	0.02	0.64	0.008	0.037	0.238
25	0.21	0.01	0.45	0.006	0.024	0.285
	0.34	0.01	0.53	0.004	0.034	0.429
	0.14	0.23	0.57	0.012	0.018	0.245

compositions, observing the macro- and micro-structure and conducting tensile tests. Further, potential for performing nondestructive evaluations, including the Vickers hardness test, and their reliability is discussed.

2. Experiment and analysis

The specimens (thickness, t = 10, 15, 20, 25 mm, material = JIS SS400) were cut from the penstock of a hydroelectric power plant located in Tokushima prefecture, Japan (Figs. 1 and 2), the characteristics of penstock are provided in Table 1. These specimens were employed in a series of experiments and were subjected to extensive analyses.

2.1. Chemical compositions

Chemical compositions were measured at 1/4 of specimen thickness (1/4 t) and the results are shown in Table 2. According to JIS standard of JIS G3101-1952, $P < 0.06\%$ and $S < 0.06\%$ are prescribed for SS400. Therefore, the obtained data is satisfactory. Further, variations in C and Ceq (carbon equivalent, Ceq = C + Si/24 + Mn/6) content are shown in Fig. 3. This result clearly illustrates that chemical compositions varies significantly across specimens. Accordingly, it is difficult to assess the material properties of the entire structure based on the specimens cut solely from a specific site.

2.2. Macro- and micro-structure observations

According to the macroscopic observations (Fig. 4), widespread yet slightly corroded area was observed on the surface of the analyzed specimens. Further, the streaked pattern (Fig. 4(b)) and the segregated area were observed inside the specimens, which would be associated with the variation in chemical compositions (cf. Fig. 3). Microscopic observations Figs. 5 and 6 showed the typical ferrite and perlite structure of SS400. The perlite content at the specimen surface was lower than that at 1/4 t and 1/2 t. Further, differences in the chemical compositions and material hardness were noted between the surface and the interior of all analyzed specimens.

2.3. Tensile tests

The tensile tests were conducted by following JIS Z2201 and 1A-type specimens were used (Fig. 7). Fig. 8shows the frequency of ultimate tensile strength,$\sigma_B$and 0.2% proof strength,$\sigma_{0.2}$, respectively. Concerningσ_B(Fig. 8(a)), some measurements revealed $\sigma_B = 389{\sim}393$ MPa, which is below the lower limit of $\sigma_B = 400$ MPa prescribed by JIS G31012. These unsatisfactory findings pertained to about 30% of the full specimen set (60 specimens). The approximation using the Gumbel distribution exhibited similar tendency. Further, $\sigma_{0.2}$ of all specimens exceeded the lower bound prescribed by JIS, and the Gumbel distribution exhibited similar tendency. As previously noted, Fig. 3 shows large variations in C and Ceq content for t = 25 mm. Corresponding large variations in σ_B and $\sigma_{0.2}$ for t = 25 mm can be observed in Fig. 9. This implies that C and Ceq content can serve as a reliable estimate of the material strength, σ_B and $\sigma_{0.2}$. Finally, irrespective of their large variations depicted in Fig. 8 a strong positive correlation between σ_B and $\sigma_{0.2}$ was observed (correlation coefficient = 0.927) in Fig. 9.