Cryogenic fatigue behaviour of steel-concrete composite structures

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Abstract. Aiming to the application of steel-concrete composite structures in extremely cold zones, a special cryogenic test equipment was developed to simulate the temperature environment along Qinghai-Tibet railway, and cryogenic fatigue tests were carried out on 10 specimens composed of 14MnNbq steel, Φ22 studs and C50 concrete. Taking temperature variation and steel rolling direction into consideration, fatigue failure mode and fatigue behaviour of the composite structures under low-temperature were well studied. Test results were compared with that under normal temperature. Results showed that composite structures performed better cryogenic fatigue performance with temperature ranging from 0℃ to -50℃, the lower the temperature is, the longer the fatigue life tends to be. This is due to the excellent cryogenic fatigue performance of 14MnNbq steel. Steel rolling direction has important influence on the fatigue behaviour of composite structures, specimens with along rolling steel girders showed longer fatigue life than those with transverse rolling steel girders. Welding Φ22 studs on 14MnNbq steel girders showed no influence on the material quality of 14MnNbq steel. For safety purpose, fatigue bearing capacity of Φ22 studs in Qinghai-Tibet railway composite bridges was suggested to be 80% of that under normal temperature.

1. Introduction
The Qinghai-Tibet railway is located in cold areas of Qinghai-Tibet Plateau. Abominable climate condition and inconvenient traffic brought great difficulties to the construction and maintenance of bridges along the Qinghai-Tibet railway. Compared with concrete bridges, steel-concrete composite bridges showed advantages in light self-weight, low noises, good earthquake-resistant performance, convenient transportation, quick construction and so forth. Therefore, deck steel-concrete composite bridges were adopted in some sections of Qinghai-Tibet railway, such as high-intensity seismic zones and cross sections of Qinghai-Tibet highway [1].

The minimum temperature along Qinghai-Tibet railway is down to -45℃. Previously, composite bridges had not ever been used in such a cold region in China. As it well known, besides steel quality, low temperature, stress concentration, welding residual stress and welding faults are also main causes of steel brittle fracture [2]. The co-action of steel and concrete of composite bridges relies entirely on shear connectors. Due to welding residual stress and welding faults, stress concentration at the roots of headed studs is very serious even in normal working condition. On the other hand, live load of railway bridges occupies a major part of the total load, fatigue resistance of the bridges is very important. For composite bridges in Qinghai-Tibet railway, with long term action of live load under low temperature,
safety and reliability of welding lines at stud roots, fatigue performance of studs, feasibility of the
design parameters under normal temperature are all the problems need careful consideration.

At present, research about the performance of composite structures and shear connectors under low
temperature is seldom reported. Soviet Union had introduced brittle fracture strength concerning low
temperature in the design codes for steel structures announced in 1982. Apart from this, neither design
provisions about steel structures nor design specifications of composite structures and shear
connectors under low temperature can be found in any bridge codes. Strict fatigue strength check
regarding to stud weld was required in both BS5400 and AASHTO, but with different methods. In
addition, it was required to check the influence of shear connectors to fatigue resistance of steel flange
in AASHTO.

Qinghai-Tibet railway composite bridges were composed of 14MnNbq steel, Φ22 stud and C50
concrete. Here, 14MnNbq steel is a new kind of bridge steel developed in China, which was used
successfully in Wuhu Yangtze River Rail-cum-Road Bridge [3]. Based on 16Mnq steel, contents of C,
S and P in 14MnNbq were decreased and a minute amount of Nb was added. After normalize
tempering, carbonitride granules were created by the combination of Nb with C and N. The granules
were dispersed in the steel evenly so that the strength, ductility and weldability of 14MnNbq steel
were improved a lot [3-5]. Even so, cryogenic brittle fracture will still happen to 14MnNbq steel
because of unavoidable micro-cracks. With long term action of live load under low temperature, the
influence of welding studs on 14MnNbq steel quality needs experimental investigation.

Up to now, researches on cryogenic brittle fracture of steel is quite few, how temperature variation
caused ductile-brittle transition to fracture toughness of material is still lack of definite theoretical
explanation. Experimental researches aiming to bridges under low temperature were only limited to
tensile tests on small component specimens, and little fatigue data was achieved [6-8]. Limited by test
condition, research results about cryogenic performance of practical structures are more deficient.
Therefore, cryogenic experimental study on composite structures is not only necessary for the
construction of Qinghai-Tibet railway, but also for the technical reserve about low-temperature
performance of composite structures.

In the presented paper, fatigue performance of 14MnNbq steel under low temperature was
elaborated in details, a special set of experimental equipment with the lowest temperature of -50℃
was designed, and the fatigue test were carried out on 10 test specimens composed of 14MnNbq steel,
Φ22 studs and C50 concrete. Fatigue damage form, fatigue life and correlative influence factors of
composite structures under low temperature was well studied.

2. Mechanical performance of 14MnNbq steel under low temperature

Destruction of steel can be divided into ductile fracture damage and brittle fracture damage. Ductile
fracture is often accompanied by large deformation so that it is easy to be found to take control
measures as early as possible. Brittle fracture often causes disastrous damage without any omen.
Except for steel quality, "low temperature" is one of the main reasons leading to brittle fracture. Here,
"low temperature" means temperature below -15℃ [9]. Brittle failure caused by low temperature
called "low-temperature cold brittleness".

Being a kind of new micro alloy steel, due to trace elements of Nb and almost zero content of S,
14MnNbq steel offers excellent weldability, lamellar tearing resistance, fatigue resistance and low
temperature impact toughness [10], shown as in Table 1. Quite a lot of research demonstrated that
small amount of Nb can improve the strength and low-temperature impact toughness of steel [11-14].

Aiming to the application in Qinghai-Tibet railway composite bridges, series of tests were carried
out on the cryogenic fatigue performance of 14MnNbq steel. Trials have concluded that:

1. Under - 50℃ low temperature, base mental and welded components of 14MnNbq steel showed
higher fatigue life cyclic than under normal temperature. Whether under normal temperature or low
temperature, fatigue life cyclic of the base mental is the lowest, welding line the secondly, welding
fusion line the highest.
Table 1. Chemical composition and Mechanical performance index of 14MnNbq steel.

| Chemical ingredient | Content | Mechanical index | Value  |
|---------------------|---------|------------------|--------|
| C                   | 0.14    | $\sigma_s$ (MPa) | 390    |
| Si                  | 0.38    | $\sigma_b$ (MPa) | 535    |
| Mn                  | 1.43    | $\delta_5$ (%)   | 32     |
| P                   | 0.012   | impact toughness | 155    |
| S                   | 0.006   | under -40°C $A_{kv}$ (J) | 126    |
| Nb                  | 0.021   |                  | 116    |

2. Whether under normal temperature or low temperature, no matter fatigue cracks occurred in base mental, welding line or fusion line, development of the crack growth rate is same.

3. Same as that under normal temperature, the higher the stress level is, the shorter the cryogenic fatigue life of 14MnNbq steel will be. Moreover, under low temperature, the influence of average loading stress on the fatigue life of 14MnNbq steel is more sensitive than that under normal temperature.

4. Yield strength and ultimate strength of 14MnNbq steel are improved with temperature decreasing. At -50°C, the two mechanical indexes were respectively increased 4.4% and 7.6% than that under normal temperature. Yield ratio was slightly decreased with no significant laws.

Taking series of cryogenic test results of 14MnNbq steel and practical low-temperature fracture examples of steel bridges into consideration, the fatigue allowable stress of 14MnNbq steel was suggested to be 20% off when the steel was applied in Qinghai-Tibet Railway steel bridges for the sake of safety.

3. Fatigue test under low temperature

3.1 Low-temperature test equipment

A special set of low-temperature equipment was developed to simulate the low temperature environment along Qinghai-Tibet railway, see figure 1 and figure 2. The equipment was mainly composed of refrigeration system, low temperature oven and temperature control system with the lowest temperature of -50°C. The bottom plate of the oven can bear load up to 1000 kN.

Before experiments, test specimens were set vertically on center of the bottom bearing plate, then another bearing plate was put on the top of the test specimens. A steel dowel was pressed on the top bearing plate through the reserved square hole in the top cover of the oven. Load was transferred in the following way: jack $\rightarrow$ steel dowel $\rightarrow$ top bearing plate $\rightarrow$ steel girder of the test specimens $\rightarrow$ studs in the concrete slab $\rightarrow$ concrete slab of the test specimens $\rightarrow$ bottom bearing plate $\rightarrow$ ground foundation. Test specimens had to be pre-cooled in the low temperature oven over 15 hours to keep temperature of the concrete slabs same as steel girders.

3.2 Test specimens

Push-out test method was adopted. Test specimens were manufactured according to the provisions of BS5400 and ECCS [7]. It is regulated in BS5400 that $d/t$ should be no more than 1.5 for tensile steel, no more than 2.0 for non-tensile steel. Here, $d$ is the stud diameter, $t$ is the plate thickness. For Qinghai-Tibet Railway composite bridges, $\Phi$ 22 studs were used; top flange thickness of the steel girder was more than 24mm. For security reasons, 20mm 14MnNbq steel were used for steel girders of the test specimens. Figure 3 showed dimensions of the test specimens.
Steel plate of the test specimens was divided into two kinds, along rolling and transverse rolling. The former means load direction is along with the steel rolling direction, the later means perpendicular.

Referring to the prescribed limits of ‘the most high water-cement ratio and minimum dosage of cement of different concrete’ in Durability Technology Conditions of Concrete in Permafrost Regions of Qinghai-Tibet Railway Plateau (Manuscript), the mix ratio of C50 concrete was determined after repeated contrast tests. See Table 2. The actual measured cubic concrete compressive strength was listed in Table 3. It was found that the concrete strength grew slowly in early curing but keep increasing even after 28 days, and measured concrete strength under low temperature was higher than that under normal temperature. Some of the completed test specimens were showed in figure 4.

| Table 2. Mix ratio of C50 concrete. |
|------------------------------------|
| Ingredient | Content |
|------------|---------|
| Cement     | 420     |
| Fly ash    | 50      |
| Siliceous dust | 25     |
| Water      | 163.3   |
| Sand       | 610     |
| Gravel     | 1115    |
| Antifreeze | 9       |
Table 3. Actual measured cubic concrete compressive strength of C50.

| Days                  | $f_c$ (MPa) |
|-----------------------|-------------|
| 28 days\textsuperscript{a} | 58          |
| 50 days\textsuperscript{a} | 65          |
| 50 days\textsuperscript{b} + 4 days\textsuperscript{b} | $> 70$      |
| 50 days\textsuperscript{a} + 4 days\textsuperscript{b} + 2 days\textsuperscript{a} | 60          |

\textsuperscript{a} Under normal temperature.
\textsuperscript{b} Under low temperature of -50°C.

3.3 Test method

Before the start of fatigue test, load-slip curve of the test specimens should be measured under static load first. The maximum static load was the upper limit of the fatigue load amplitude, which was applied to test specimens with multi-stages. After that, the test specimens were put into the low-temperature test equipment.

Relative slip on the interface of concrete slab and steel girder was measured by dial indicators. The magnetic stand of the dial indicator was fixed on the flange of the steel girders, and the indicator was pointed to a small piece of thin steel sheet glued on the concrete slabs. During fatigue test, to avoid being frozen in the low temperature oven, dial indicators must be taken off from the test specimens as soon as each measurement finished. Consequently, due to the lack of benchmark, it was failed to determine the absolute value of the relative slip between concrete and steel, only slip amplitude $\Delta s$ can be measured according to the swing of pointer.

During fatigue tests, the side door of the low-temperature oven was opened at regular intervals, the dial indicator was installed on the test specimen, and then $\Delta s$ was measured. That was the way to get $N-\Delta s$ curve. Here, $N$ is the number of fatigue cycles. A specimen in test was showed in figure 5.

![Figure 5. Specimen in test.](image)

3.4 Test results and analysis

There are 10 specimens in total for the fatigue test, named D1 ~ D10. Test results showed in Table 4.

3.4.1 Fatigue life under low-temperature. In low temperature environment above -50°C, specimens D1, D2, D7, D8 remained intact after over $200\times10^4$ fatigue cycles. Specimen D5 remained intact under -50 °C with $201\times10^4$ fatigue cycles, but was finally destroyed after another $3.19\times10^4$ fatigue cycles under room temperature. Compared the test results of D7 ~ D10, it was found that, with same load...
amplitude, under low-temperature between -50°C and 0°C, the lower the temperature was, the better the fatigue performance of test specimens tended to be.

Table 4. Fatigue test results under low temperature (C50, Φ22, 14MnNbq).

| Test specimens | Steel rolling direction | Fatigue load range ΔP (kN) | Fatigue stress amplitude Δσ (MPa) | Temperature | Fatigue life N | Remarks |
|----------------|-------------------------|-----------------------------|----------------------------------|-------------|----------------|---------|
| D1             | Along                   | 78~250                      | 113.12                           | -50°C, with 5 cycles range from -50°C to NT | 270×10⁴       | remained intact |
| D2             | Along                   | 78~300                      | 146.01                           | -50°C       | 202×10⁴       | remained intact |
| D3             | Transverse              | 78~360                      | 185.46                           | -50°C       | 126.25×10⁴    | destroyed    |
| D4             | Along                   | 78~360                      | 185.46                           | NT          | 67.7×10³      | destroyed    |
| D5             | Along                   | 78~360                      | 185.46                           | -50°C       | (201+3.19)×10⁴ | remained intact after 201×10⁴ cycles, stop refrigerating and keep blowing, destroyed after another 3.19×10⁴ cycles under room temperature |
| D6             | Transverse              | 78~360                      | 185.46                           | NT          | 14.07×10⁴     | destroyed    |
| D7             | Along                   | 78~360                      | 185.46                           | -50°C       | 210×10⁴       | remained intact |
| D8             | Along                   | 78~360                      | 185.46                           | -25°C       | 201×10⁴       | remained intact |
| D9             | Along                   | 78~360                      | 185.46                           | 0°C         | 74×10⁴        | destroyed    |
| D10            | Along                   | 78~360                      | 185.46                           | -10°C       | 209.9×10⁴     | destroyed    |

3.4.2 Failure mode. Failure mode of the destroyed test specimens in the low-temperature fatigue test was illustrated in figure 6. It can be seen that studs were snapped off at roots on the tensile side along load direction, and a piece of base mental welded with studs was also pulled off. It demonstrated that fatigue life of studs under low temperature is controlled by heat affected zone at stud roots.

3.4.3 Influence of steel rolling direction. Steel rolling direction showed great influence on the fatigue life of test specimens. Shown as Table 4, specimens with along rolling steel girders have much longer fatigue life than that with transverse rolling steel girders.

Figure 6. Failure mode of studs in cryogenic fatigue test (specimen D3).

3.4.4 N-Δs curves. Figure 7 showed N-Δs curves of test specimens in low-temperature fatigue test. It can be seen that slip amplitude Δs increased with the increasing of fatigue cycles N, but the regularity displayed inconspicuously. During the fatigue test, test specimens were almost destructed when Δs
was measured increasing quickly. The maximum measured $\Delta s$ of the test specimens was about 0.4mm before cryogenic fatigue destruction.

4. Compared with test results under normal temperature

According to table 4, D4 and D6 were tested under room temperature, D3 and D5, under -50°C. Among the four test specimens, steel girders of D4 and D5 are along rolling direction, D3 and D6, transverse rolling direction. Test results of the four specimens showed that, with same fatigue load amplitude, D4 and D6 performed longer fatigue life than D3 and D5. Namely, as composite structures composed with 14MnNbq, $\Phi22$ studs and C50 concrete to be concerned, with same fatigue load amplitude, fatigue life under room temperature is much shorter than that under low-temperature.

To make further comparison, fatigue tests under room temperature were carried out on another 6 specimens with an appropriate decrease of fatigue load amplitude. Test results were listed in Table 5, specimens named S1~S6 in sequence. Comparing Table 5 with Table 4, it was found that fatigue life of composite structures composed of 14MnNbq, $\Phi22$ studs and C50 concrete under low-temperature was longer than that under room temperature, even if the load amplitude was decreased somewhat. See figure 8.

The above test results are mainly related to the excellent cryogenic fatigue performance of 14MnNbq steel. As mentioned in Section 2, cryogenic fatigue life of 14MnNbq steel and welding components is much better than that under normal temperature. Besides, cryogenic fatigue strength of 14MnNbq steel will decrease with the increasing of average loading stress. Therefore, for safety purpose, fatigue bearing capacity of $\Phi22$ studs in Qinghai-Tibet railway composite bridges was suggested to be 80% of that under normal temperature.

| Test specimens | Steel rolling direction | Fatigue load range $\Delta P$(kN) | Fatigue stress amplitude $\Delta \tau$(MPa) | Fatigue life N | Fatigue strength ratio
|----------------|------------------------|---------------------------------|---------------------------------|----------------|-----------------------|
| S1             | Along                  | 78~230                          | 99.97                           | 232.0×10⁴      | 91.5×10⁴              |
| S2             | Along                  | 78~250                          | 113.12                          | 174.0×10⁴      | 96.5×10⁴              |
| S3             | Transverse             | 78~290                          | 139.43                          | 225.0×10⁴      | 102.5×10⁴             |
| S4             | Transverse             | 78~300                          | 146.01                          | 240.0×10⁴      | 108.0×10⁴             |
| S5             | Along                  | 78~320                          | 158.91                          | 250.0×10⁴      | 115.0×10⁴             |
| S6             | Along                  | 78~330                          | 165.74                          | 255.0×10⁴      | 117.5×10⁴             |

Table 5. Fatigue test results under room temperature (C50, $\Phi22$, 14MnNbq).

**Figure 8.** Comparison of the fatigue test results under room temperature and low-temperature

5. Conclusions
1. With same fatigue load amplitude, composite structures composed of 14MnNbq steel, Φ22 studs and C50 concrete perform longer fatigue life under low-temperature ranging from -50°C to 0°C than under room temperature. The lower the temperature is, the longer the fatigue life tends to be.

2. Fatigue life of Φ22 studs is controlled by heat affected zone at stud roots, no matter under low-temperature or room temperature. Steel rolling direction has great influence on the fatigue life of composite structures. Specimens with along rolling steel girders have much longer fatigue life than that with transverse rolling steel girders.

3. Good cryogenic fatigue performance of composite structures is due to the excellent cryogenic material quality of 14MnNbq steel. For safety purpose, fatigue bearing capacity of Φ22 studs in Qinghai-Tibet railway composite bridges was suggested to be 80% of that under normal temperature.

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