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BOND STRESS-SLIP OF STRAND IN PRESTRESSED CONCRETE SLEEPERS

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Continuous vertical force on sleepers gradually degrades the bonding between the concrete and the prestressing strands. In particular, the vertical wheel loads can be significantly amplified due to irregularities on the wheel or on the track. This can eventually result in cracking or splitting of concrete along the strands leading to the structural failure of concrete sleepers. The bond between strand and concrete is an important factor which can directly or indirectly influence the cracking and splitting failure of the sleeper. This paper reports a series of pullout tests undertaken on specimens with 85 MPa concrete (nominal strength) and 7-wire prestressing strands replicating typical prestressed concrete sleepers produced in New Zealand. The results are discussed and compared in terms of the loads causing the first strand slip and also the bond stress – slip relationship. The results show that longer water curing time does not necessarily increase the bond between strand and concrete in prestressed concrete sleepers. This behaviour can be attributed to the effect of shrinkage and the trade-off between strength and shrinkage influenced by water curing. The obtained results can contribute to determining optimum sleeper curing time to achieve required strength and bonding and is valuable for concrete sleeper manufacturers where curing process is associated with considerable cost and logistical issues.

Keywords: Sleeper failure, Prestressing strands, Pullout test, Strand slip.

1 INTRODUCTION

Railway prestressed concrete sleepers are located between the rail and ballast in transverse direction to the rail. The sleepers transfer the loads from the rail to the track substructure and also restrain the rail in the lateral, longitudinal and vertical directions. Concrete sleepers experience high magnitudes of shear force and bending moment under repeated vertical loads from the passing trains which can result in structural failures such as different cracking, rail seat crushing and strand slippage in the sleeper. In particular, the vertical loads are significantly increased at the sleepers next to the rail welds or rail joints or in vicinity of other rail and wheel surface irregularities due to high wheel-rail forces. The bond of steel bars or strands with concrete is an important factor, which can affect the performance and durability of concrete sleepers. For deformed bars and strands embedded in concrete, the bond is described as the transfer of force from the reinforcement to the surrounding concrete through adhesion, friction and mechanical interlock.

In this paper, the loading and failure mechanisms of prestressed concrete sleepers are briefly reviewed, and the importance of strand bond is discussed. Next, a series of the pullout tests used to investigate bond behaviour of prestressing strand are presented. The general testing process is based on ASTM A1081/A1081M (2012) and AS/NZS 4672.1 (2007). This study is a part of an ongoing research on the failure of concrete sleepers and track support damages and its effect on the loads and progressive deterioration of track.

2 LOADING AND FAILURE OF PRESTRESSED CONCRETE SLEEPERS

A view of a prestressed concrete sleeper in rail track is shown in Figure 1. Sleepers are subject to a high cycle of vertical loads due to the running trains. The vertical wheel load can vary from 25kN to 150kN depending on the train type and its properties (Esveld 2001). These vertical loads generate a bending moment in sleeper where the bending scenario is dependent upon the sleeper-ballast contact pressure distribution. The pressure distribution beneath the sleeper and in turn the sleeper bending scenario is highly variable depending on the track substructure condition (Sadeghi 2008); therefore, causing variability in the location of peak bending stresses along the sleeper in different rail tracks.

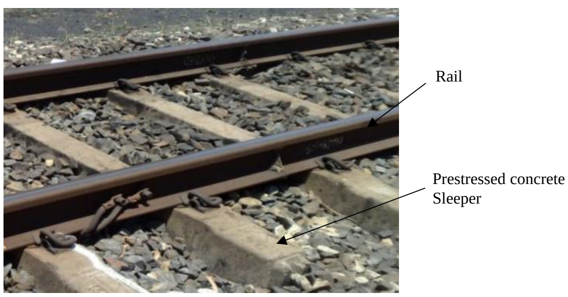


Figure 1. Typical prestressed concrete sleeper in railway track.

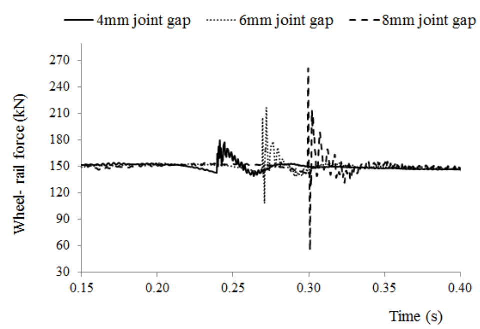
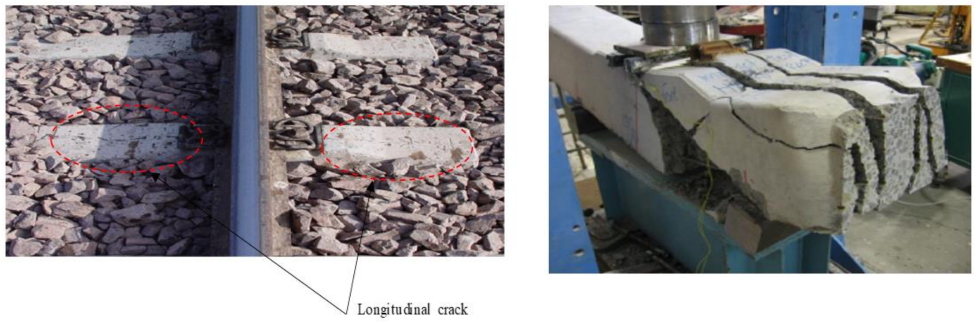


Figure 2. Typical wheel-rail force amplification at a rail joints (Askarinejad and Dhanasekar 2016).

Additionally, the vertical wheel loads may be significantly amplified due to irregularities on the wheel or on the track. This includes wheel flats, rail surface corrugation and roughness, rail welds, rail joints and track geometry irregularities. The dynamic wheel load amplifications have been studied by many researchers. For examples, Grossoni *et al*. (2013) and Askarinejad and Dhanasekar (2016) are among the recent ones presenting simulation and experimental results for wheel-rail forces at rail joints. Figure 2 shows a sample wheel-rail force scenario at a rail joint. It can be seen that the vertical force can reach nearly double the static wheel load at the rail joints. This value can be significantly higher when the rail joint is located on a track geometry dip. Moreover, some studies have reported much higher vertical forces generated due to wheel flats; for instance, a wheel-rail force of 600 kN due to 20-25 mm wheel flats (Kaewunruen and Remennikov 2009).

Considering the repetitive and high magnitudes of forces, the adjacent concrete sleepers can get severely damaged. Various types of damage or failure have been reported in the literature such as rail seat deterioration, cracking in different locations along the sleeper as well as splitting and strand slip within the concrete (Thun *et al*. 2008, Lutch *et al*. 2009, Kaewunruen and Remennikov 2013, Zakeri and Rezvani 2012, Taherinezhad *et al*. 2013). Figure 3 shows two sample sleeper failure types.



a) Longitudinal crack (Zakeri and Rezvani 2012 b) Splitting failure (Kaewunruen and Remennikov, 2013)

Figure 3. Longitudinal crack and splitting failure along the strands in prestressed concrete sleeper.

The bond between strand and concrete is an important factor which can directly or indirectly influence the cracking and splitting failure of the sleeper. Insufficient strand bond can adversely affect the overall flexural performance of the sleeper resulting in various flexural cracks. These cracks may also gradually aggravate under repeated loads leading to the splitting along the strands. The concrete-steel bar bond in various applications have been investigated by many researchers. For example, Hadi (2008) conducted a series of pull out tests using specimens fabricated with steel bars ranging from 12mm to 36 mm. He also looked into the effect of concrete cover around the bar using 240 mm and 300mm diameter concrete cylinders. Lim *et al.* (2013), studied the bond behavior and transfer length of prestressing strands using experimental and finite element analyses. Dang *et al*. (2014) investigated the correlation of strand surface quality and bond strength. They concluded that the lubricants and residue chemicals that accuse the variation may reduce bond between concrete and steel bar. Additionally, some researchers have focussed on the bond stress and strand slip behaviour in special or newly emerged concrete materials such as geopolymer concrete and self-consolidation concrete. Kim and Park (2015) studied the bond properties of reinforcements embedded in Geopolymer Concrete. Looney *et al*. (2012) reported an experimental study on bond strength of reinforcing steel in self-consolidating concrete.

This paper reports a series of pullout tests undertaken on specimens with 85 MPa concrete (nominal strength) and 7-wire prestressing strands replicating typical prestressed concrete sleepers produced in New Zealand. The results provide good information on strand stress-slip magnitudes in a typical prestressed concrete sleeper, which will be useful in understanding strand slippage failure behaviour. Additionally, particular attention is paid to the effects of sleeper curing condition on the strand bond as curing is a major logistical aspect of prestressed concrete production process.

3 BOND SLIP TEST

The test specimens were produced with dimensions of 150x150x450 mm using 85MPa concrete (nominal strength) and 7-wire prestressing strands. Considering suitable dimensions and embedment length are critical to obtain the expected bond stress-slip behaviour. For example, if the embedded length of the bar is not suitable, the strand may yield and fail before slipping through the concrete. The bond stress acts parallel to the bar along the concrete interface (Figure 4). Therefore, assuming uniform stress distribution, the bond stress (u) can be calculated as the average stress between the reinforcing bar and the surrounding concrete along the embedded length of the bar as below:

$$u = \frac{F}{\pi L d_b} \tag{1}$$

Where, F is the pullout force, L is the strand embedded length in the concrete, and d_b is the strand diameter. The specimens were fabricated in a prestressed concrete plant in Christchurch, NZ. The strands were 7-wire low relaxation strand with a diameter of 8mm and cross section area of 38.82 mm^2. The ultimate tensile strength and yield strength of the strand are 2060MPa and 1967MPa respectively and elongation ratio is 3.79%. The concrete was placed into the moulds in a number of layers where each layer of concrete was vibrated and compacted thoroughly with the penetrating vibrator. After 24 hours, the moulds were removed and the specimens were split into four groups (three specimens in each group). The first group (Group A) was kept in room temperature. The second group (Group B) was kept in room temperature for 21 days and then placed in a water tank for 7 days. The third group (Group C) was kept in room temperature for 14 days and then in water tank for 14 days. The fourth group (Group D) was cured in a water tank for 28 days. The tests were undertaken using an Avery Universal Testing Machine (UTM) at Ara's Engineering Laboratory. The concrete blocks were attached under the cross-bar where the strand was clamped on the top of the machine. A dial gauge was clamped at the bottom end of the strand to measure the strand slip.

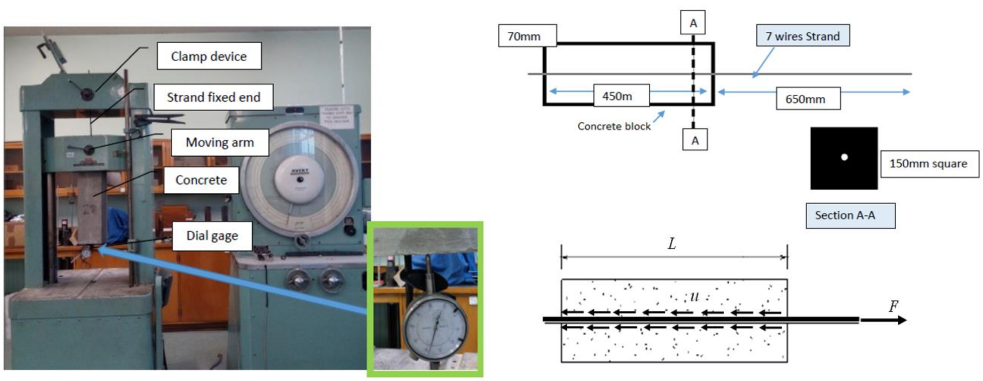


Figure 4. Test setup and the specimens' size and dimensions.

Figure 4 demonstrates one of the test specimens, which has been set up ready for testing. As shown in this figure, the test specimens were suspended via the strand. Moving UTM table upwards would force the test specimens against the underside of the stationary cross-bar. Once the specimens rested against the cross-bar, a pullout force would be applied to the strand. The load was applied with the loading rate of 0.1kN/s.

4 TEST RESULTS AND DISCUSSION

The pullout forces and the corresponding gauge readings were recorded. The loading stopped when the strand slip reached about 1mm. The same procedure was repeated for each specimen. Observation of the specimens after the tests shows the damage at the strand-concrete interface due to the strand slip as expected. Figures 5 presents the magnitudes of pullout force, which caused the first slip in the strands.

It can be seen in Figure 5 that the first slip occurred at higher loads in the Groups B and D specimens compared to other groups. The pullout force causing the first slip in the strands in these two groups are measured between 45 kN and 55 kN. Figure 6 shows the bond stress vs strand slip comparing the bond stress-slip relationship for the groups of specimens. All three curves show a nonlinear pattern up to about 0.2mm slip where low rate of slip is observed for high values of bond stress. When the slip exceeds 0.2mm, the strand slip increases nearly linearly as the bond stress rises.

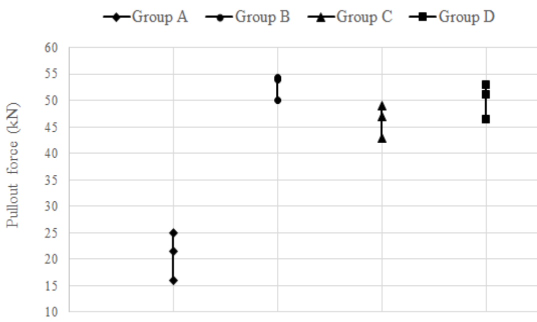


Figure 5. Pullout force at the first slip.

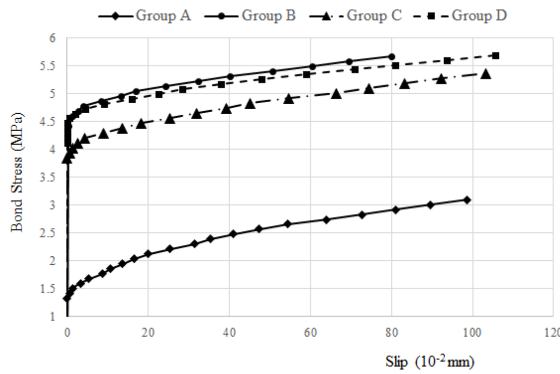


Figure 6. Bond stress vs strand slip.

It is interesting to see that Group B samples (with 7 days water curing) show consistently higher bond stress with magnitudes very close to Group D (with 28 days curing). This shows that longer water curing time does not necessarily increase the bond between strand and concrete in prestressed sleepers. This behavior can be attributed to the effect of shrinkage.

It should be noted that moist curing could have two significant effects on concrete. The moist curing would harden the cement paste and thus increases the concrete strength as well as the concrete-steel bond; additionally it would decrease the shrinkage. Even though shrinkage can cause problems such as dimensional changes, it can be beneficial to increase the concrete-steel bond. Concrete shrinkage would cause the concrete to grip the strands more tightly, increasing the friction and hence increase the bond between concrete and strand. This means there is an optimum curing time to achieve the required compressive strength and strand bond; such that whichever is dominate (concrete strength effect or shrinkage effect) would determine if the longer moist curing would increase or decrease the bond between concrete and steel. This result can contribute to determining optimum sleeper curing time to achieve required strength and bonding and is valuable for concrete sleeper manufacturers where curing process is associated with considerable cost and logistical issues.

In the next stage, further research is in progress to link the measured bond stress-slip with the vertical wheel loads applied to the sleeper in track and the strand slippage failure mechanism. In addition, it should be noted that a damaged sleeper can cause a progressive rise in wheel-rail forces and subsequent damages to the surrounding sleepers and the underlying substructure.

5 CONCLUSIONS

As part of an ongoing research, an attempt has been made to investigate strand bond behavior of the prestressed concrete sleepers. Strand bond is an important factor, which can control the performance of concrete sleepers in track where high magnitudes of shear force and bending moment are generated under wheel loads. Lab experiments were undertaken to determine the relationship between bond stress and strand slip in specimens with high strength concrete and 7-wire prestressing strands replicating typical prestressed concrete sleepers produced in New Zealand. This was done by measuring the strand movement (slip) under pullout force. The measured bond stress-slip showed a nonlinear pattern up to about 0.2 mm slip and then the strand slip increased almost linearly as the bond stress increased. The tests provided interesting results where the specimens that water cured for 7 days showed bond stress as high as the ones cured for 28 days, which was attributed to the effects of concrete shrinkage.

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