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# Effect of groove spacing on bond strength of near-surface mounted (NSM) bonded joints with multiple FRP strips

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## HIGHLIGHTS

- A 3-D finite element model is developed for NSM bonded joints with two FPP strips.
- The groove spacing effect on bond strength is clarified through parametric study.
- Reduction factors are formulated to consider the groove spacing effect.
- A bond strength model is proposed for NSM bonded joints with multiple FPP strips.

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## ABSTRACT

In the strengthening of existing deficient structures using the near-surface mounted (NSM) FRP method, a group of parallel NSM FRP strips are usually needed to meet the capacity enhancement requirement. When the groove spacing (i.e., the net distance between grooves) is relatively small, the bond behaviour of each NSM FRP strip is detrimentally influenced by the adjacent grooves/FRP strips, and such detrimental effect should be taken into account for a safe design of the NSM FRP strengthening system. All the existing models, however, have been proposed for NSM bonded joints with a single FRP strip and thus cannot consider the effect of groove spacing on the bond behaviour, due to the insufficiency of data from tests or numerical simulations. Against this background, a numerical parametric study, was conducted to clarify the effect of groove spacing on the bond strength of such bonded joints; the numerical parametric study involved the use of a three-dimensional meso-scale finite element model developed in the present study for NSM bonded joints with two FPP strips separately embedded in two parallel grooves. Based on the results from the parametric study, a reduction factor to account for the detrimental effect of insufficient groove spacing on the bond strength is proposed and extended to NSM bonded joints with three or more evenly-spaced FRP strips. By combining the proposed reduction factor and the bond strength model previously developed by the authors for NSM bonded joints with a single FRP strip, a bond strength model for NSM bonded joints with multiple FRP strips is proposed and the accuracy of the proposed model is verified with test results.



## 1. Introduction

The Near-surface mounted (NSM) fiber-reinforced polymer (FRP) strengthening technique, as a promising alternative to the externally bonded (EB) FRP method for structural strengthening, has attracted worldwide attention over the last decade. Compared with the EB FRP method, the NSM FRP method has a number of advantages, including a higher bonding efficiency and a better protection of the FRP reinforcement [1]. FRP bars of various cross-sectional shapes (e.g. square, round and rectangular bars) have been studied by researcher as NSM FRP reinforcement. Existing experimental studies have showed that compared with other cross-sectional shapes, FRP strips (i.e., rectangular bars with a large aspect ratio) possesses a much better bonding efficiency (i.e., a higher local bond strength and a higher interfacial fracture energy), as they have a larger perimeter-to-cross-sectional area ratio and a larger embedment depth [e.g. 2–5]. In terms of material type, carbon FRP (CFRP) are thought to be more attractive than other types of FRP for the application of NSM strengthening technique, as CFRP usually has a higher strength and stiffness and thus could lead to a small cross-sectional area with the same demand in load-carrying capacity. Therefore, CFRP strips have become very popular for the use in NSM FRP strengthening and have attracted a large number

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of studies [e.g. 1,5–7]. As one of the fundamental issues in the application of NSM FRP strengthening method, the bond strength, which is the maximum force that can be developed in the FRP reinforcement in the test of bonded joints [e.g. 8,9], has been studied by a number of researchers, and several bond strength models have been proposed for NSM FRP-to-concrete interfaces by directly regressing test results on NSM FRP-to-concrete bonded joints [e.g. 10,11] or conducting a numerical parametric study [e.g. 12,13]. All the existing models, however, were proposed for a single FRP strip NSM to concrete and thus have not taken into account the effect of groove spacing (i.e., the net distance between grooves $a_g$, as shown in Fig. 1) on the bond behaviour. In real application of NSM FRP strengthening method, including flexural strengthening and shear strengthening of RC members, a group of parallel NSM FRP strips (as shown in Fig. 1) need to be applied to meet the capacity enhancement requirement, and their bond behaviour may be detrimentally influenced by the adjacent grooves/FRP strips. The detrimental effect of insufficient groove spacing on the bond behaviour between NSM FRP reinforcement and concrete has not yet been clarified.

## 2. Detrimental effect of insufficient groove spacing

When a group of two FRP strips (separately embedded in two parallel grooves) are used in the NSM strengthening method, the detrimental effect of insufficient groove spacing on the bond behaviour of each FRP strip only exists on the side where the adjacent FRP strip (referred to as adjacent FRP side for simplicity) is embedded. The bond behaviour on the other side (referred to as outer side for simplicity) is free from such detrimental effect, and thus the bond strength contributed from the outer side can be assumed to be half of the bond strength of NSM bonded joints with a single FRP strip. The difference between the total bond strength of each FRP strip and the bond strength contributed from the outer side is just the bond strength contributed from the adjacent FRP side. A reduction factor to account for such effect on the bond strength can therefore be obtained, i.e., the ratio between the bond strength from the adjacent FRP side and half of the bond strength of NSM bonded joints with a single FRP strip. This reduction factor can be extended to situations where a group of three or more FRP strips (embedded in evenly-spaced parallel grooves) are used. Among these FRP strips, each of the two outmost FRP strips suffers the detrimental effect of insufficient groove spacing from one side and thus the reduction factor only needs to be applied on one side in the calculation of the bond strength of each FRP strip, while each of the inner FRP strips suffers such detrimental effect from both sides and thus the reduction factor needs to be applied on both sides in the calculation of the bond strength of each FRP strip.

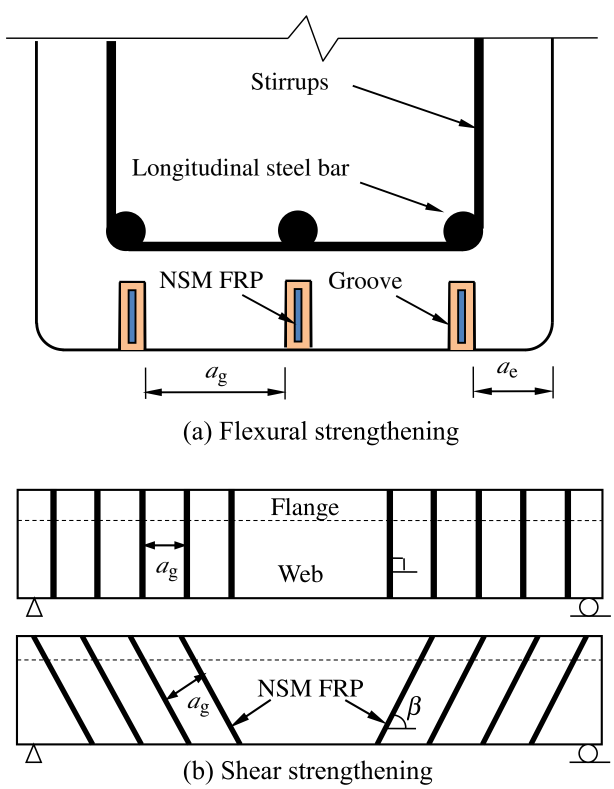


**Fig. 1.** Strengthening of RC beams using NSM FRP method.

Against the above background, a three-dimensional (3-D) meso-scale finite element (FE) model of bonded joints with two CFRP strips is developed, based on the FE model established by Teng et al. [14] for bonded joints with a single CFRP strip whose accuracy has been verified with experimental results. A numerical parametric study, covering the most important parameters, is conducted in the present paper by adopting the developed FE model. Based on the results of the parametric study, a reduction factor is proposed to account for the effect of groove spacing on the bond strength. By introducing the proposed reduction factor into the bond strength model previously proposed by the authors (Zhang et al. [13]) for bonded joints with a single FRP strip, a new bond strength model is established for bonded joints with multiple FRP strips. The performance of the new bond strength model is then assessed with the existing test results.

## 3. Finite Element (FE) model

### 3.1. General

Based on the 3-D meso-scale model developed by Teng et al. [14] for the single-lap shear test of NSM FRP strips-to-concrete bonded joints (referred to as NSM bonded joints hereafter for simplicity) with a single FRP strip, the FE model for NSM bonded joints with two FRP strips separately embedded in two parallel grooves (referred to as NSM bonded joints with two FPP strips hereafter for simplicity) was built in the present study, using the software package MSC.MARC [15]. It has been proved that the FE model established by Teng et al. [14] can well predict the failure process and ultimate load of NSM bonded joints with a single FRP strip, as well as the strain distributions of the FRP and the local bond-slip relationship between NSM FRP strip and concrete [14]. The failure mechanism of the current case is the same as that modelled in [14], with the only difference being that two FRP strips instead of one need to be included in the built FE model. Failure of NSM bonded joints may happen in the materials (i.e., FRP, adhesive and concrete) or at FRP-to-adhesive/concrete-to-adhesive interfaces [13,14]. However, it has been widely accepted that in practical applications, it should be guaranteed that the final failure is controlled by the failure in concrete as otherwise the strengthening efficiency cannot be maximized. Existing experimental studies, in fact, have proved that cohesive failure in concrete can be ensured by using an appropriate adhesive (usually with a tensile strength much higher than the concrete) and by carrying out appropriate surface preparation before application [13]. Therefore, in the numerical simulation of NSM bonded joints, the accurate modelling of concrete material is of critical importance. Following Teng et al. [14], the modelling of concrete, in particular the tensile and shear behavior of the cracked concrete, was carefully treated in the present study. The well-established tension-softening curve