Near Surface Mounted GFRP Strips: An Overview

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Abstract— The use of glass fiber-reinforced polymer (GFRP) materials for strengthening bridges and buildings has been used extensively in the last decade. Glass fiber reinforced polymer has been used in different configurations and techniques to use the material effectively and to ensure long service life of the selected system. One of these innovative strengthening techniques is the near-surface mounted (NSM) that consists of placing Glass fiber reinforced polymer reinforcing bars or strips into grooves pre-cut into the concrete cover in the tension region of the concrete member. This method is relatively simple and considerably enhances the bond of the mounted Glass fiber reinforced polymer reinforcements, thereby using the material more effectively. NSM Glass fiber reinforced polymer reinforcing bars and strips is practical, significantly improves the stiffness, and increases the flexural capacity of reinforced concrete beams. Strengthening of reinforced concrete beams using NSM Glass fiber reinforced polymer strips provided higher strength capacity than externally bonded FRP strips using the same material with the same axial stiffness. Issues raised by the use of NSM GFRP reinforcement include the optimization of construction details, models for the bond behaviour between NSM GFRP and concrete, reliable design methods for flexural and shear strengthening, and the maximization of the advantages of this technique. This paper provides a critical review of existing research in this area, identifies gaps of knowledge, and outlines directions for further research.

Key words: NSM; GFRP; FRP

I. Introduction

Glass fiber-reinforced polymer (GFRP) reinforcement is used for new construction as well as for strengthening and repair of existing concrete structures. Externally bonded Glass fiber reinforced polymer sheets and strips are one of the techniques used for flexural and shear strengthening of concrete beams and slabs. Several researchers reported that the failure of members strengthened with externally bonded Glass fiber reinforced polymer sheets and strips could be brittle due to debonding or peeling of the Glass fiber reinforced polymer reinforcements, especially in the zones of high flexural and shear stresses. Externally bonded Glass fiber reinforced polymer reinforcements could be highly susceptible to damage from collision, fire and temperature, ultraviolet rays, and moisture absorption. In the NSM method, grooves are first cut into the concrete cover of an RC element and the FRP reinforcement is bonded therein with proper groove filler (typically epoxy paste or cement grout). What is herein called ‘‘NSM reinforcement’’ was previously given other names such as ‘‘grouted reinforcement’’, or ‘‘embedded reinforcement’’. The advantages of GFRP versus steel as NSM reinforcement are better resistance to corrosion, increased ease and speed of installation due to its lightweight, and a reduced groove size due to the higher tensile strength and better corrosion resistance of GFRP. NSM GFRP method is in many cases superior to the externally bonded GFRP method or can be used in combination with it, provided that the cover of the member is sufficiently thick for grooves of a desirable size to be accommodated. Configuration of the glass fiber reinforced polymer reinforcements used for the near surface mounted technique is controlled by the depth of the concrete cover. This paper focuses on research work on the structural aspects of NSM strengthening of concrete structures.

II. Literature Review

The use of Near Surface Mounted glass fibre reinforced polymer reinforcement for strengthening is relatively recent. Asplund [1] carried out tests on concrete beams strengthened with near surface mounted steel bars grouted into diamond-sawed grooves filled with cement mortar and compared their behaviour with that of conventional concrete beams reinforced with steel bars. Identical behaviour for both sets of specimens was observed. The same technique was used in strengthening a reinforced concrete bridge deck in Sweden that experienced excessive settlement of the negative moment reinforcement during construction, so that the negative moment capacity needed to be increased.

De Lorenzis, Nanni and La Tegola [2] showed that NSM carbon fibre reinforced polymer sandblasted rods and deformed glass fibre reinforced polymer rods increased the flexural strength of simply supported reinforced concrete T-beams by 30 and 26%, respectively. Increasing the amount of NSM reinforcement did not produce significant gain in the capacity.

Arduini, Gottardo, and DeRiva [3] found that the use of high-strength mortar with compensated shrinkage or epoxy putty guarantee full use of the NSM FRP strengthening system.

Carolin, Hordin, and Tiiljsten [4] concluded that ultimate load carrying capacity of beams strengthened with rectangular NSM carbon fibre reinforced polymer rods using epoxy adhesive and cement grout as bonding agent has increased by 77 and 56%, respectively. Using high-strength rectangular NSM FRP rods and high modulus rectangular NSM FRP rods increased the ultimate load capacity by 108 and 93%, respectively. Prestressed NSM carbon fibre reinforced polymer rectangular rods have been used as a bonded post-tensioned system to strengthen concrete beams. The initial strain was approximately 0.002, which is about 12% of the ultimate strain. The beam strengthened with prestressed NSM carbon fibre reinforced polymer rods showed about a 100 and 37% increase in the cracking and yielding load, respectively, compared with the beam strengthened with non prestressed NSM carbon fibre reinforced polymer rods. The ultimate loads and failure modes were the same with or without prestress by rupture of the NSM FRP rods; however, beams prestressed with NSM carbon fibre reinforced polymer rods had smaller deflections at failure.

Hassan [5] investigated the performance of various NSM fibre reinforced polymer reinforcing bars and strips, as well as externally bonded fibre reinforced polymer sheets on small scale concrete beams and slabs, including cost analysis for each of the fibre reinforced polymer strengthening techniques. Test results showed that using NSM carbon fibre reinforced polymer reinforcing bars increased the strength by 36%. Using NSM carbon fibre reinforced polymer strips increased the strength by 43% in comparison with an increase of only 11% using the axial stiffness used as externally bonded strips due to peeling failure of the strips. He reported that the efficiency of using fibre reinforced polymer reinforcing bars as NSM reinforcement is controlled by the bond characteristics of the reinforcing bars in addition to the bond between the epoxy adhesive material and the surrounding concrete in the groove. He also reported that such a limiting value is highly dependent on the configuration and the ratio of the steel reinforcement inside the concrete beam as well as on the stress level at the concrete-epoxy interface. The author found that the maximum measured tensile strain in the carbon fibre reinforced polymer bars at failure is in the range of 40 to 45% of the rupture strain of reinforcing bars, and that the rupture of carbon fibre reinforced polymer reinforcing bars is not likely to occur regardless of the embedment or bond length or the type of epoxy adhesive used.

De Lorenzis, and Nanni A [6] showed advantage of using glass fibre reinforced polymer instead of steel is primarily due to its corrosion resistance, which is particularly important in this case due to the location of the reinforcing bars or strips being very close to the surface that could be exposed to aggressive environmental attacks. The maximum tensile strain in the carbon fibre reinforced polymer and glass fibre reinforced polymer bars used as NSM reinforcement did not exceed 33 and 60% of the rupture strain of the bars at failure, respectively.

Raafat EI-Hacha, Sami H. Rizkalla [7] has presented an analytical investigation conducted to study the flexural behaviour of reinforced concrete beams strengthened with various Near-Surface-Mounted (NSM) Fiber-Reinforced Polymers (FRP) reinforcements. The following conclusion had drawn from his investigation. Strengthening concrete beams with NSM FRP reinforcements increased the flexural stiffness and the ultimate load carrying capacity of the strengthened beams compared to the unstrengthened beam and to the strengthened beams with externally bonded FRP reinforcement. For the beams strengthened with various NSM FRP reinforcements, the predicted load-midspan deflection curves agreed very well with the experimental results in both the linear (prior to concrete cracking) and non-linear ranges. The load-tensile strain curves for the various NSM FRP reinforcements showed good agreement between the experimental results and the prediction from the non-linear analytical model. Both the predicted load-midspan deflection and load-tensile strain in the various FRP reinforcements have similar trends with those obtained from the experimental results. The iterative non-linear analytical model used in this study demonstrated very well the behaviour of the concrete beams and provided better understanding of the NSM FRP strengthened concrete beams. The analytical model can be used to conservatively estimate the load-carrying capacity of concrete beams strengthened with NSM FRP reinforcements. The model can be used to develop design guidelines for strengthening reinforced concrete beams with NSM and externally bonded FRP reinforcements.

Soliman et al [8] executed a study on the flexural behaviour of concrete beams strengthened with NSM-FRP bars. A total of 20 reinforced concrete beams were tested. The beams were separated into three different series (A-C), with the internal reinforcement ratio increasing with each series (0.4%, 0.8%, and 1.6%). The beams all had dimensions of 200 mm in width, 300 mm in depth, and 3010 mm in length. Also the bonded length of the NSM bars was increased within each series, as well as the type of NSM bars being changed between carbon and glass FRP. The carbon fibre reinforced polymer bars used had two different diameters, 9.5 and 12.7 mm, while the glass fibre reinforced polymer bars had a diameter of 12.7 mm. Only a single groove was cut into each of the beams in order to strengthen them with the NSM bars. The beams were tested in four-point bending over a simply-supported span of 2.6 m, until failure at a rate of 1.2 mm/min. All of the strengthened beams had a failure mode of cover delamination, starting at the cut-off points of the NSM-FRP bars. From the results, several things can be concluded. One conclusion is that using the NSM-FRP bars is an efficient way to increase the flexural capacity and stiffness of concrete beams. The increase of bond length will result in an increase in capacity, up to a limit of approximately 48 times the bars diameter. The NSM-FRP bars system was more effective with beams with low reinforcement ratios. Also, the glass fibre reinforced polymer bars showed similar increases in the beams' carrying capacities to those of carbon fibre reinforced polymer bars. In the beams with a steel reinforcement ratio of 0.4%, the strengthened beams showed an increase in total applied load capacity over the control beam ranging from 22 to 104%.

Tarek H. Almusallam et. al. [9] has investigated the effectiveness of NSM bars as a means of restoring or upgrading the flexural capacity of RC beams experimentally and numerically. The studied parameters included type of NSM bars: steel versus GFRP, and NSM reinforcement ratio (number and diameter of inserted NSM bars). A total of eight groups of 16 beams were tested under four-point bending. The two beams of the first group were reinforced with three main steel bars and were used as control specimens. The two beams of the second group were reinforced with three main GFRP bars and were utilized for comparison with control specimens. Assuming that one of the three main steel bars in the control specimen had corroded, three groups of six beams were designed in which one NSM steel or GFRP bar was inserted in the tension side. Yet, with the assumption of the corrosion of two main steel bars in the control beam, the last three groups of six beams were planned in which two NSM steel or GFRP bars were planted in the tension side. For NSM-upgraded beams, special type of epoxy paste was used as bonding agent. Test results showed that by using NSM steel or GFRP bars to compensate the difference in the main reinforcement, the original load capacity of the control beam was successfully restored. The ultimate capacity of the beams was predicted using the ACI 318-11 code and ACI 440.1R-06 guidelines. A numerical investigation utilizing nonlinear finite element (FE) analysis was also carried out using LS-DYNA software. A comparison was made between the experimental and numerical results and good agreement was obtained. Based on the validation of FE results, the numerical analysis was extended to include additional cases to study the effect of FRP reinforcement ratio on the flexural performance of NSM-upgraded beams. He concluded that the bond behaviour of all planted steel and GFRP bars was excellent, in which no debonding or bond failure was observed in any of the tested beams. This is attributed to the sufficient end anchorage of the NSM bars in addition to the good bonding of the epoxy adhesive used in this study.

I. A. Sharaky, L. Torres, J. Comas, C. Barris [10] were experimentally investigated the behaviour of RC beams strengthened with NSM FRP bars. Eight beams were tested under four point bending. The effects of material type, epoxy properties, bar size and the number of NSM bars were studied. The tested beams were strengthened with a limited bond length in order to imitate as much as possible work-place conditions, as the grooves could only be cut up to the faces of the supporting columns with difficulty. The load capacity, deflection, mode of failure, FRP strain, concrete strain, free end slip and the transverse strain in epoxy and concrete of the tested beams were all analyzed. Comparison of strengthened and control beams showed enhancement of 155.8% and 129.8% in the yielding loads, while the increase in the ultimate loads was 166.3% and 159.4% for beams strengthened with carbon fibre reinforced polymer and glass fibre reinforced polymer respectively. The beams strengthened with bars experienced higher stiffness than the corresponding beams with bars. Epoxy properties, size and number of bars had little effect on the load capacity of the strengthened beams with failures mainly occurring either in epoxy or as a result of concrete cover separation.

III. MATERIALS AND SYSTEMS

A. *GFRP Reinforcement*

GFRP bars can be manufactured in a virtually endless variety of shapes. Hence, the NSM GFRP reinforcement may be round, square, rectangular and oval bars, as well as strips (Figs. 1 and 2). For brevity, the term ‘‘bars’’ is used herein as a generic term encompassing all cross-sectional shapes, while the term ‘‘strips’’ is reserved for thin narrow strips. Different cross-sectional shapes have different advantages, and offer different choices for practical applications. For example, square bars maximize the bar sectional area for a given size of square groove while round bars are more readily available and can be more easily anchored in pre-stressing operations. Narrow strips maximize the surface area-to-sectional area ratio for a given volume and thus minimize the risk of debonding, but require a thicker cover for a given cross-sectional area. In practical applications, the choice depends strongly on the constraints of a specific situation, such as the depth of the cover, and the availability and cost of a particular type of GFRP bar. GFRP bars are also manufactured with a variety of surface textures, which strongly affect their bond behaviour as NSM reinforcement. Their surface can be smooth, sand-blasted, sand-coated, or roughened with a peel-ply surface treatment. Round bars can also be spirally wound with a fiber tow, or ribbed [11].

Fig. 1: Types of FRP bars ans strips.

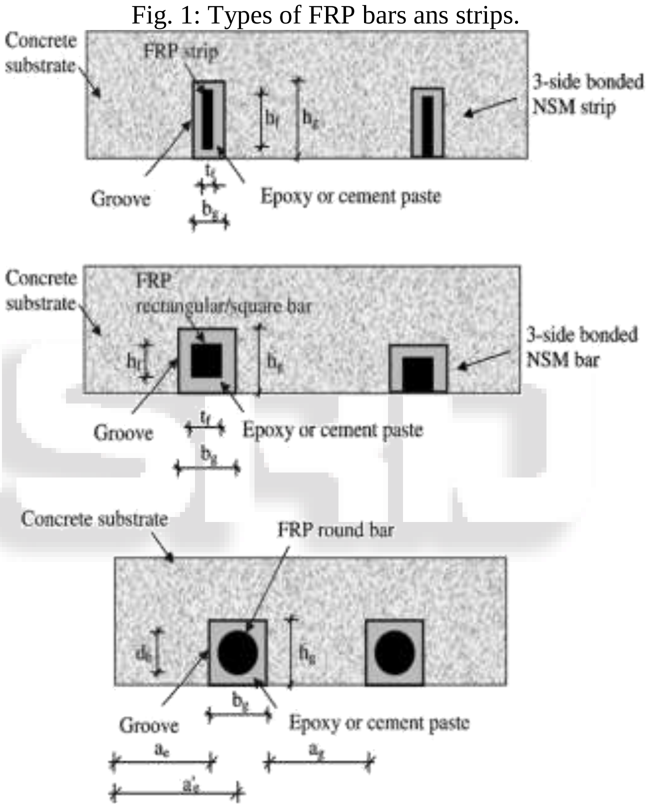

Fig. 2: Different NSM systems and nomenclature.

B. *Groove Filler*

The groove filler is the medium for the transfer of stresses between the GFRP bar and the concrete. In terms of structural behaviour, its most relevant mechanical properties are the tensile and shear strengths. The tensile strength is especially important when the embedded bars have a deformed surface, which produces high circumferential tensile stresses in the cover formed by the groove filler (simply referred to as ‘‘the cover’’ or ‘‘the epoxy cover’’ hereafter) as a result of the bond action. In addition, the shear strength is important when the bond capacity of the NSM reinforcement is controlled by cohesive shear failure of the groove filler. The effect of the modulus of elasticity of the groove filler has never been experimentally investigated. The most common and best performing groove filler is a two-component epoxy. Low-viscosity epoxy can be selected for strengthening in negative moment regions as the epoxy can be ‘‘poured’’ into the grooves. For other cases, a high-viscosity epoxy is needed to avoid dripping or flowing-away. The addition of sand to epoxy can increase the volume, control the viscosity, lower the coefficient of thermal expansion, and raise the glass transition temperature. A drawback of this addition seems to be reduced adhesion at the bar–epoxy interface for a smooth bar surface.

The use of cement paste or mortar in place of epoxy as a groove filler has recently been explored in an attempt to lower the material cost, reduce the hazard to workers, minimize the environmental impact, allow effective bonding to wet substrates, and achieve better resistance to high temperatures and improved thermal compatibility with the concrete substrate. However, cement mortar has inferior mechanical properties and durability, with a tensile strength an order of magnitude smaller than that of common epoxies. Results of bond tests and flexural tests [12,13] have identified some significant limitations of cement mortar as a groove filler.

C. Groove Dimensions

Fig. 2 shows several configurations of NSM FRP reinforcement, where db is the nominal diameter of a round bar, and tf and hf are the thickness/width and the height of an FRP strip or rectangular bar respectively. The groove width bg, the groove depth hg, the net distance between two adjacent grooves ag, and the net distance between a groove and the beam edge ae are all relevant construction parameters, which can influence the bond performance and hence the structural behaviour. For round bars, De Lorenzis [14], based on results of bond tests with square grooves (bg = hg) and defining k = bg/db, proposed a minimum value of 1.5 for k for smooth or lightly sand-blasted bars and a minimum value of 2.0 for k for deformed bars. Parretti and Nanni [15] suggested that both bg and hg should be no less than 1.5db. For NSM strips, Blaschko [16] suggested that the depth and width of the cut groove should be about 3 mm larger than the height and thickness of the corresponding FRP strip respectively, so to obtain an adhesive layer thickness of about 1–2 mm. Also for NSM strips, Parretti and Nanni [15] recommended that the minimum width of a groove be no less than 3tf and the minimum depth be no less than 1.5hf. In the existing studies, NSM strips were bonded using epoxy either along all four sides of the strip surface, or along three sides of the strip surface only (Fig. 2). Due to the large width to thickness ratio of the strips, the reduction in the bond surface in the latter case is negligible. In existing tests on NSM square bars, only three sides of the bar surface were bonded to the concrete member.

D. Groove Position

If a single NSM bar is to be provided to the tension side of an RC member, it should naturally be centrally located over the beam width. When two or more NSM bars need to be provided, then the distance between two adjacent NSM bars and the distance between the edge of the member and the adjacent bar become important design parameters.

IV. FLEXURAL STRENGTHNING

All existing test results of strengthened beams, slabs, and columns indicate that the NSM reinforcement improved the ultimate load and the load at the yielding of steel reinforcement, as well as the post-cracking stiffness. One study [7] has compared equivalent amounts of NSM reinforcement provided as round bars or strips. As expected, strips performed better and failed by tensile rupture as opposed to debonding of the round bars, as a result of the higher local bond strength and larger lateral surface to cross-sectional area ratio of NSM strips.The possible failure modes of beams flexurally-strengthened with NSM GFRP reinforcement are of two types: those of conventional RC beams, including concrete crushing or GFRP rupture generally after the yielding of internal steel bars, for which the composite action between the original beam and the NSM GFRP is practically maintained up to failure, and ‘‘premature’’ debonding failure modes which involve the loss of this composite action. Although debonding failures are less likely a problem with NSM GFRP compared with externally bonded FRP, they may still significantly limit the efficiency of this technology. The likeliness of a debonding failure depends on several parameters, among which the internal steel reinforcement ratio, the GFRP reinforcement ratio, the cross-sectional shape and the surface configuration of the NSM reinforcement, and the tensile strengths of both the epoxy and the concrete. There is still limited understanding of the mechanics of debonding in beams strengthened with NSM systems. Descriptions of failure modes in the existing literature are often not sufficiently detailed to understand the progression of the failure process.

V. CONCLUSION

Strengthening of structures with NSM GFRP reinforcement is a technique that has attracted a considerable attention as a feasible and economic alternative to the former techniques of strengthening structures. Research on the strengthening of structures using NSM GFRP reinforcement started only a few years ago but has by now attracted worldwide attention. A significant amount of research has been conducted on this emerging technique, particularly on the application of this technique in the strengthening of concrete structures. This paper has provided a detailed and critical review of existing research on the flexural behaviour of concrete structures strengthened with NSM GFRP reinforcement. This review has shown that the existing work is still limited in both scope and depth, and many questions remain to be answered before the technique can be widely accepted by practicing engineers. Based on this review, the more urgent research needs have been outlined for NSM GFRP strengthening of concrete structures.

A. Research Needs

The Obviously, given the larger number of parameters that can affect the flexural behaviour of RC beams with NSM GFRP reinforcement, a great deal of further experimental and theoretical work is required. In particular, the debonding failure mechanisms in beams strengthened with NSM reinforcement need to be clarified through further testing. The relationship between concrete cover separation and other modes of debonding ‘‘local’’ to the NSM GFRP–concrete joint such as fracture at the epoxy–concrete interface and splitting of the epoxy cover needs further research. Furthermore, the behaviour of pre-damaged beams strengthened with NSM GFRP is of significant practical interest, as cracking and damage to the cover of the steel reinforcement may have a significant effect on the debonding failure process. The relationship between bond failure mechanisms in bond test specimens and debonding failure mechanisms in flexurally-strengthened beams needs to be clarified by detailed experimental studies as well as rigorous theoretical modelling. Here, the study of the interaction between flexural/flexural-shear cracking and bond stresses is of crucial importance. Once this relationship is clarified, it will then be possible to develop numerical and analytical models for predicting debonding failures.

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REFERENCES

[1] Asplund SO "Strengthening Bridge Slabs with Grouted Reinforcement," J Am Concr Inst, vol. 20(6), pp. 397-406, 1949
[2] De Lorenzis L, Nanni A, La Tegola A, "Flexural and shear strengthening of reinforced concrete structures with near surface mounted FRP rods," ACMBS III, Ottawa (Canada),2000, pp.521-528.
[3] Arduini M, Gottardo R, De Riva, "FRP Rods for Flexural Reinforcement of Existing Beams: Experimental Research and Applications," Proceedings of the International Conference on FRP Composites in Civil Engineering, V. 2, Hong Kong, China, 2001, pp. 1051-1058.
[4] Taljsten B., Carolin A., "Concrete Beams Strengthened with Near Surface Mounted CFRP Laminates," Proceedings of the 51th International Conference Fibre-Reinforced Plastics for Reinforced Concrete Structures, V. I, Cambridge, UK, 2001, pp. 107- 116.
[5] Hassan T. K., "Flexural Performance and Bond Characteristics of FRP Strengthening Techniques for Concrete Structures," PhD thesis, Department of Civil and Geological Engineering, University of Manitoba, Winnipeg, Manitoba, Canada, 2002, pp. 304.
[6] De Lorenzis L., Nanni A., "Bond between Near-Surface Mounted FRP Rods and Concrete in structural Strengthening," ACI Structural Journal, 99(2), Mar.-Apr. 2002, pp. 123-132.
[7] Raafat EI-Hacha, Sami H. Rizkalla, "Near-Surface-Mounted Fiber-Reinforced Polymer Reinforcements for Flexural Strengthening of Concrete Structures" ACI Structural Journal, 101(5), Sep-Oct 2004, pp.717-726.
[8] S. M. Soliman, E. EL. Salakay, B. Benmokrane, "Flexural behaviour of concrete beams strengthened with near surface mounted fibre reinforced polymer bars" Canadian Journal of Civil Engineering, Vol. 37, 2010, pp 1371-1382.
[9] Tarek H. Almusallam, "Experimental and numerical investigation for the flexural strengthening of RC beams using near-surface mounted steel or GFRP bars", Construction and Building Materials,40, 2013, pp.145–161.
[10] I.A. Sharaky, "Flexural response of reinforced concrete (RC) beams strengthened with near surface mounted (NSM) fibre reinforced polymer (FRP) bars", Composite Structures, 109 , 2014, pp.08-22.
[11] American Concrete Institute Technical Committee 440. Guide for the design and construction of concrete reinforced with FRP bars. ACI 440.1R-03, 2003.
[12] Nordin H, Taljsten B., "Concrete beams strengthened with CFRP. A study of anchor lengths," In: Proceedings 10th conference on structural faults and repair, London (UK), 2003.
[13] Taljsten B, Carolin A, Nordin H., "Concrete structures strengthened with near surface mounted reinforcement of CFRP", Adv Struct Eng, 6(3), 2003, pp 201–13.
[14] De Lorenzis L, "Strengthening of RC structures with near surface mounted FRP rods," PhD Thesis, Department of Innovation Engineering, University of Lecce, Italy, 2002.
[15] Parretti R, Nanni A, "Strengthening of RC members using near surface mounted FRP composites: design overview," Adv Struct Eng, 2004, 7(6), pp 469–83.
[16] Blaschko M, "Bond behaviour of CFRP strips glued into slits," In: Proceedings FRPRCS-6, Singapore: World Scientific, 2003, pp 205–214.