Comments on the efficiency of closed stirrups

The stirrups, as well known, perform in two ways:

- to repair damages caused by shear, or occasionally by torque, offering several benefits such as:
    - suppressing flexural tensile stress in the cantilever blocks by means of the diagonal compression force, resulting from Mörsch truss analogy
    - limiting the opening of diagonal cracks within the elastic range, thus enhancing and preserving shear transfer by aggregate interlock
    - improving the contribution of the dowel action
- providing confinement to the longitudinal compression reinforcement and to concrete

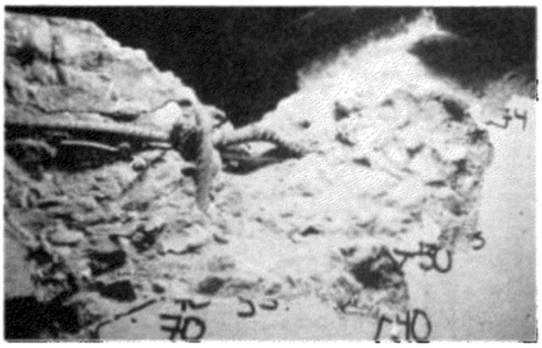


Figure 1 - Example of buckling of compression reinforcement in a beam (picture N. S. Anderson, J. A. Ramirez, “Detailing of stirrups reinforcement”, ACI Structural Journal, Vol. 86, N. 5, 1989, pag. 507-514)

Obviously, all these tasks can be performed successfully only if the stirrup is efficient, which means that it must not open up to the breaking point load.

Therefore, it is evident that the geometry of the stirrups is depending on the manufacturing technology of the beam and on the geometry of its cross section . Perhaps for this reason all the codes give few information regarding manufacturing details of the stirrups, leaving to the designer the responsibility of their efficiency. In any case, very large differences may be encountered from country to country. In figure 2, for example, are compared stirrups of a beam AASHTO-PCI Type III as specified by the Florida Department of Transportation and by the Eurocodes (F.Iorio, M.A. Pisani: “Comparative analysis of two pre-tensed bridge beams” , Industria Italiana del Cemento, magazine , July-August 2004).

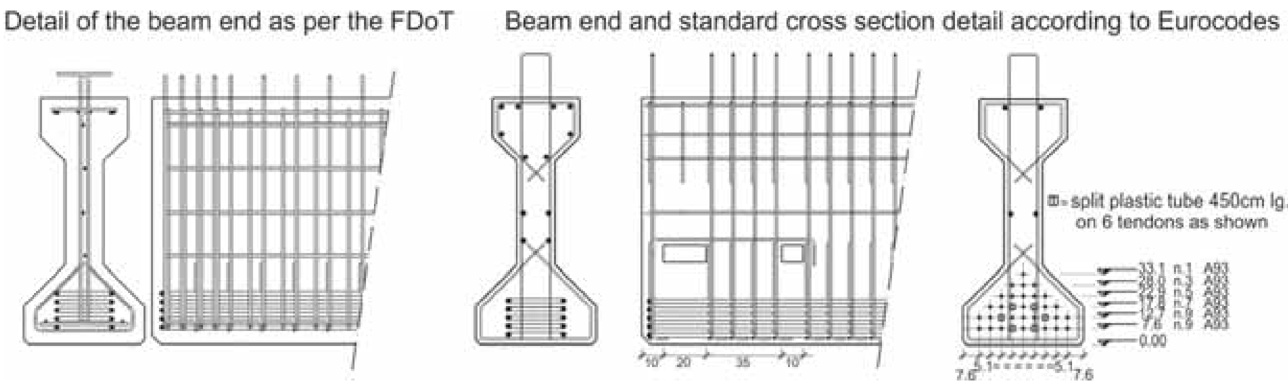


Figure 2

Dealing with wide beams in beam-slab floor systems the American standards (ACI Committee 318, "Building Code Requirements for Structural Concrete - ACI 318-08 and Commentary," American Concrete Institute, Farmington Hills, MI. Look also at "Wide Beam Stirrup Configurations", Concrete International, Vol.32, N. 3, pagg. 62-64) allow two different options:

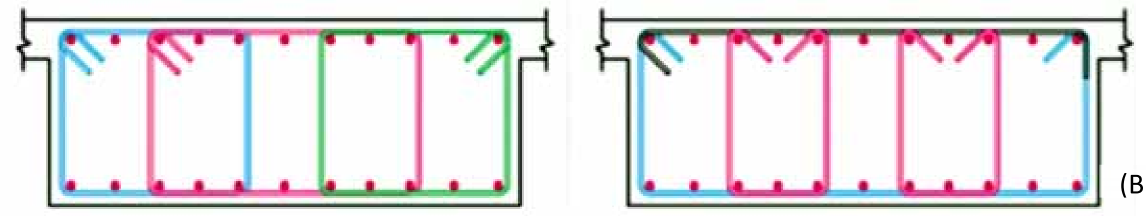
(A)  (B)

Figure 3

The stirrups in "A" are defined as "closed stirrups" both in the American Standards and in the Eurocodes. In option "B" (which allows an easier assembly of the reinforcement cage on site) the rebar shown in black in figure 3 does not confine the compression reinforcement, but is utilized only to hold together the longitudinal rebars during concrete casting. However, if the bending direction changes along the beam axis (as it happens in a continuous beam), the 135-degree hooks of the "U" shaped stirrups will be in a tensile zone with the risk of slipping-off (N.S. Anderson e J.A. Ramirez, "Detailing of stirrup reinforcement", ACI Structural Journal, Vol.86, N.5, 1989, pagg. 507-515).

In the same way, the stirrups illustrated in figure 4 have shown in actual applications not to be able to grant any confinement to the longitudinal reinforcement (and to concrete too) when the structural element is under high compression and bending (as is the case for some columns and foundation piles): as the load increases, the concrete cover will detach, leaving loose the stirrups development length, as it can be seen in figure 5.

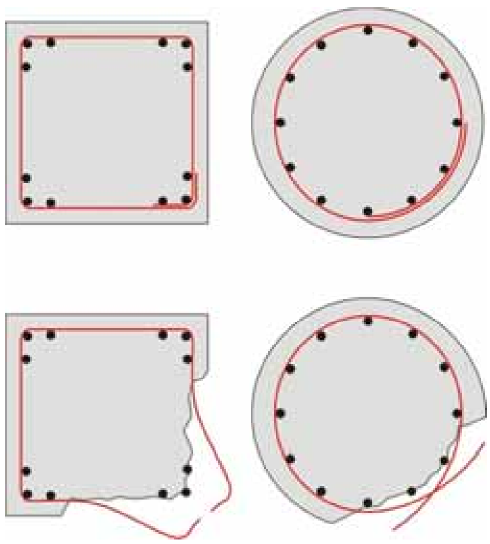


Figure 4

Figure 5 - No anchoring of the stirrups in the column core (A. Castellani, D. Benedetti, A. Castoldi, E. Faccioli, G. Grandori, R. Nova, "Costruzioni in zona sismia", Masson Italia Editore, Milan, 1981)

So, it is not casual the fact that the Italian code ("New Technical Specifications for Construction", DM 14 Gennaio 2008, G.U. n. 29, 4-Febb-2008 – Suppl. Ordinario n.30) , in the section 7.4.6.2.1 "Travi" (beams) requires that "in critical areas confining stirrups must be utilized............meaning a rectangular stirrup, or circular, or with spiral shape, with 6mm minimum diameter, with hooks at 135° extended for at least 10 diameters to each end. The hooks must be secured to the longitudinal bars. " This type of stirrup is referred to in the next section 7.4.6.2.2. "Pilastri" (columns). Moreover, discussing about piers and bridge abutments, the same code requires that (Section 7.9.6.2.) "All confining reinforcement, stirrups or ties, must end with 135° hooks anchoring towards inside for a length minimum 10 diameters".
In other words, the closed stirrup (described in figure 3A) represents generally the most efficient and accurate solution, if well manufactured (in respect of minimum bending radius, etc.)

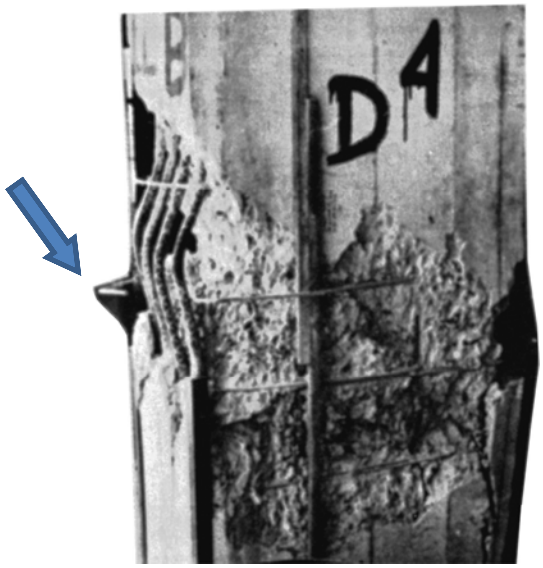


Figure 6 - Well packed stirrups. The column crashed because of the tensile failure of the stirrups. (A. Castellani, D. Benedetti, A. Castoldi, E. Faccioli, G. Grandori, R. Nova, "Costruzioni in zona sismia", Masson Italia Editore, Milano, 1981)

The stirrups described in figure 4 are just as efficient as long as the ends are welded to one-another (but quality and length of welds must be carefully checked).

Within the section enlargement there is no physical space to arrange closed stirrups with 135° hooks while "good" in situ welding is difficult and expensive; for this reason new systems have been patented to produce closed stirrups by means of mechanical fastening as illustrated in figure 7.

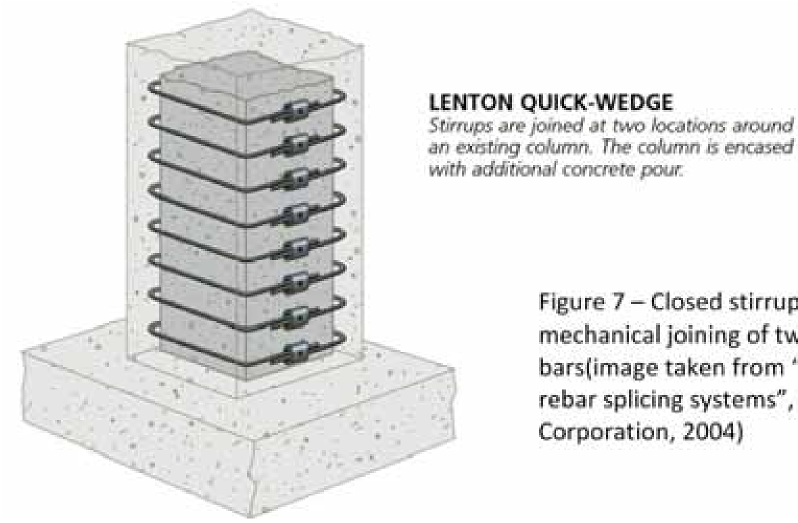


Figure 7 – Closed stirrups obtained by mechanical joining of two "U"shaped bars(image taken from "Lenton – Mechanical rebar splicing systems", ERICO International Corporation, 2004)

All above data regarding steel closed stirrups apply to GRP (glass fiber reinforced polymer) stirrups as well. Already for steel it was stated that they be “well manufactured” meaning that some specified parameters must be respected, particularly that the minimum curvature radius must be respected (in order to prevent cracks in the bar) and a sufficient level of bond of the rebars to concrete (this is a requirement for approval of the rebar). Therefore, an accurate examination of the GFRP production technology is necessary to establish and specify the parameters for “good product”.

The GFRP bars are produced by “pultrusion”, a modern, automatic, continuous production technology. The process is described in the scheme of Figure 8. This technology produces straight bars.

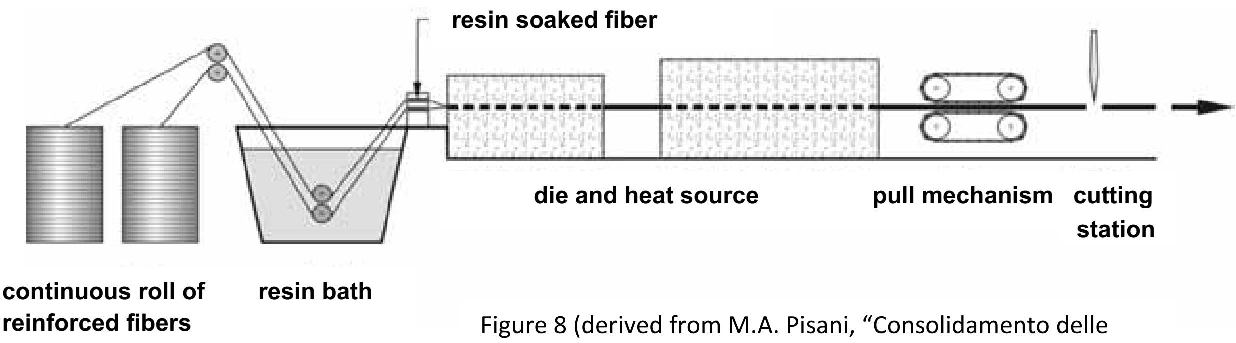


Figure 8 (derived from M.A. Pisani, “Consolidamento delle strutture”, Hoepli, Milano, 2008, pp.452)

The mechanical behaviour of the fibers is elastic-brittle, consequently it is not possible to bend the bars after the polymerization of the resinous matrix. So, it is necessary to prevent polymerization of the resin in the section to bend, to bend that section by hand, and to introduce the bent rod in an oven to complete polymerization. This solution though presents us with a problem: the fibers are initially lined in a parallel position and upon bending they tend to squeeze in one of the ways described in figure 9.

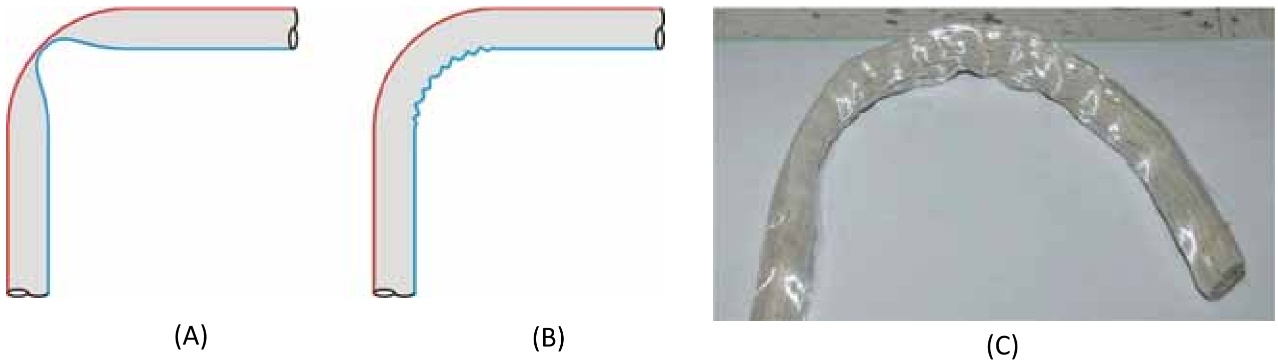
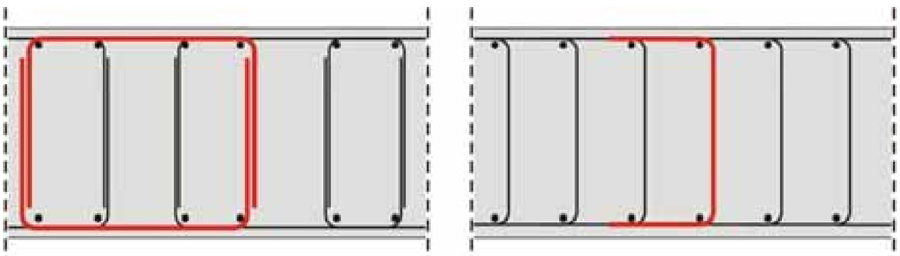


Figure 9 – Parallelism defects in the bent sections of the GFRP bars (Fig.9C is taken from: E. A. Ahmed, A. K. El-Sayed, E. El-Salakawy, B. Benmokrane, “Bend strength of FRP stirrups: somparison and evaluation of testing methods”, ASCE Journal of Composites for Construction, Vol. 14, No. 1, 2010, pag. 3-10).

To avoid this problems the bar is locally rotated (on its longitudinal axis) and then bent. But this operation will cause the majority of the fibers to assume an helical form in the inner part of the curved zone, while those in the center of the cross section will have an wavy form, resulting in a highly reduced resistance (about 50% reduction, according E.A. Ahmed, A.K. El-Sayed, E. El-Salakawy, B. Benmokrane, "Bend strength of FRP stirrups: comparison and evaluation of testing methods", ASCE Journal of Composites for Construction, Vol. 14, No. 1, 2010, pag.3-10), resistance in any case to be checked with lab tests.

A totally different case is represented by the production of closed (anular) stirrups with a targeted manufacturing system. With this technology, the fibers impregnated with resin are placed (wound) on a mould of the desired form, and then the "wet" fiber-resin system is processed for polymerization. This technology allows to grant that the fibers be all parallel, with noticeable benefits for the mechanical behaviour of the finished product. This technology offers another advantage: there are no ends to anchor to concrete.

Regarding the development length of GFRP bars, it is important to point out that their bond strength is always less than that of a ribbed steel bar. This is due to the fact that during pull-out tests bond failure of a steel bar occurs because of crushing of concrete between the ribs, while with the composite bars it is the superficial polymeric resin to detach from the inner layers of fibers, but the surrounding concrete will remain intact. For this reason also the issue of the 10 diameters extension on the 135-degree hook should be revised by organizing proper lab test to be performed on the specific product (as a matter of fact, the finish of the surface of composite bars varies greatly among available products). Moreover, the problem of the development length is critical in the case where "U" shaped stirrups coupled by simple overlapping are utilized as shown in figure 10A, while utilization of strips as shown in figure 10B is questionable from both the Italian and the American code points of view as already point out explaining figure 3B.



(A) (B)

Figure 10

These short notes are not intended for publicity of a product, but only to describe some problems related to the manufacturing technology of GFRP stirrups.

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Member of the Task Group that generated the following guideline: CNR-DT 203/2006 “Guide for the design and construction of concrete structures reinforced with Fiber-Reinforced Polymer bars”, National Italian Research Council