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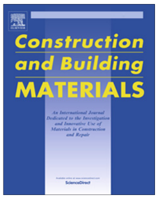

Anchorage of reinforcement bars in Hennebique structures

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HIGHLIGHTS

- Hennebique structures exhibit specific anchorage details for longitudinal bars and stirrups.
- Modern code provisions cannot be used to assess the anchorage of Hennebique structures.
- Tests on fish-tail ends and bended plate stirrups provide data for assessing these anchorages.
- Collapse mechanisms of Hennebique anchorages are identified.
- Assessment formulas for ancient anchorage systems are provided.

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ABSTRACT

A crucial aspect of the assessment of existing r.c. structures is the efficiency of the anchorage of the bars. This is specifically true for historic pre-code concrete, when the basic principles of r.c. structures were either not well understood nor set in a code practice. This is true also for the Hennebique-type structures that make use of a shape of the anchorages that falls outside modern codes. In spite some tests performed by Hennebique and his concessionaries at the times of their activity, it seems that nobody noticed that the shape of anchorages was a weak point of their system.

In this paper a series of tests have been performed on two typical Hennebique anchorages: fish-tail ends and plate stirrup bends. Tests have been performed using a Hennebique-type concrete, with similar sieve curve, low to medium strength, large round aggregates and an excess of water. The outcomes outline the collapse mechanisms of these anchorages and allow to set assessment type formulas that may be of common use in practical applications. It has to be noted that direct verifications, as large as possible, are needed when assessing a pre-code structures due to the lack or standards that characterizes pre-code r.c. structures.

1. Introduction

Even though François Hennebique was not the first to deal with concrete and reinforcing bars, no doubt that he was one of those who most affected the first years of reinforced concrete constructions [1–4]. His patent, although unclear in its theoretical basis and in several technological aspects, in many countries was the most exploited system in the first pioneering period of r.c. constructions [5–7] that ends approx. with WWI [8]. If the Hennebique system did not find space in Germany [9], it was used in U.K. due to the cooperation with Mouchel [5] and in Spain with Ribera [10] while in other countries, such as France [11], Belgium [4], and Italy [11–14] it remained the leading building system for a couple of decades.

Even though the first codes in Europe were issued before WWI, in 1903 for Switzerland, in 1904 in Germany, in 1906 for France, in 1907 for Italy, in 1908 for the USA and Russia [14–19], it took more than a decade for the patent system to be substituted by a rational approach to r.c. design. This is mainly true for those countries in which the patents remained valid till their natural expiration, such as Italy and Spain. The outcome is that Hennebique structures, or Hennebique-like structures, built till approx. the 20 s, remained un-engineered to a large extent.

Nowadays warehouses, industrial facilities, a large number of bridges and buildings, either residential and public, built according to the Hennebique system, are in service. For many of them retrofitting is needed due to several reasons, such as material degradation, re-functioning and, mainly for strategic buildings such as schools, hospitals and public offices, for their seismic upgrade.

The intrinsic weaknesses of the early reinforced concrete structures, among which the Hennebique system plays the major role, is well known and addressed by several authors [4,20–25]. Two main

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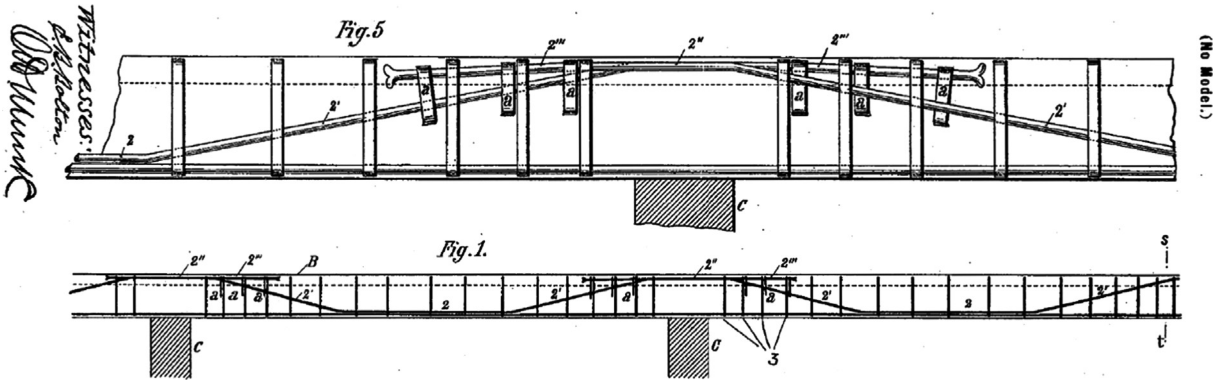

Fig. 1. Longitudinal section of a beam according to the USA Hennebique patent [30].

Fig. 2. Fish-tail ends and hooks of reinforcing bar of the slab of a villa inside the *Villa Gruber* park, Genoa (Italy), unknown building date, in-between 1900 and 1930.

Fig. 3. Load test to collapse of a T beam performed by the Porcheddu company [27] – unpublished photo.

issues need specific attention: i) concrete compressive strength, affecting the bending capacity of the beams; ii) shear capacity, which depends on the amount of shear reinforcement and on the efficiency of its anchorage.

This paper addresses a specific problem: the anchorage performance of either bending and shear reinforcing bars. Due to the reduced anchorage length, only partially compensated by the shape of the bar, it will be showed that in most cases the bending and shear capacity is limited by sliding of the bars in the anchorage regions, which is crucial when the structural performance of a Hennebique-type structure has to be estimated.

2. The Hennebique system and its points of concern

In this section the Hennebique system is discussed aiming at pointing out the key points for the safety assessment of this kind of structures.

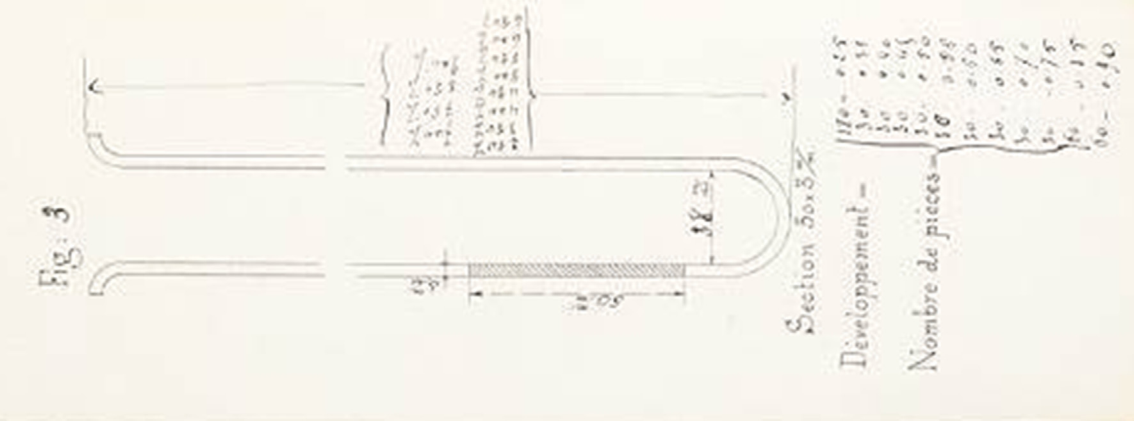

Fig. 4. Typical shape of a stirrup, 1897 [31].

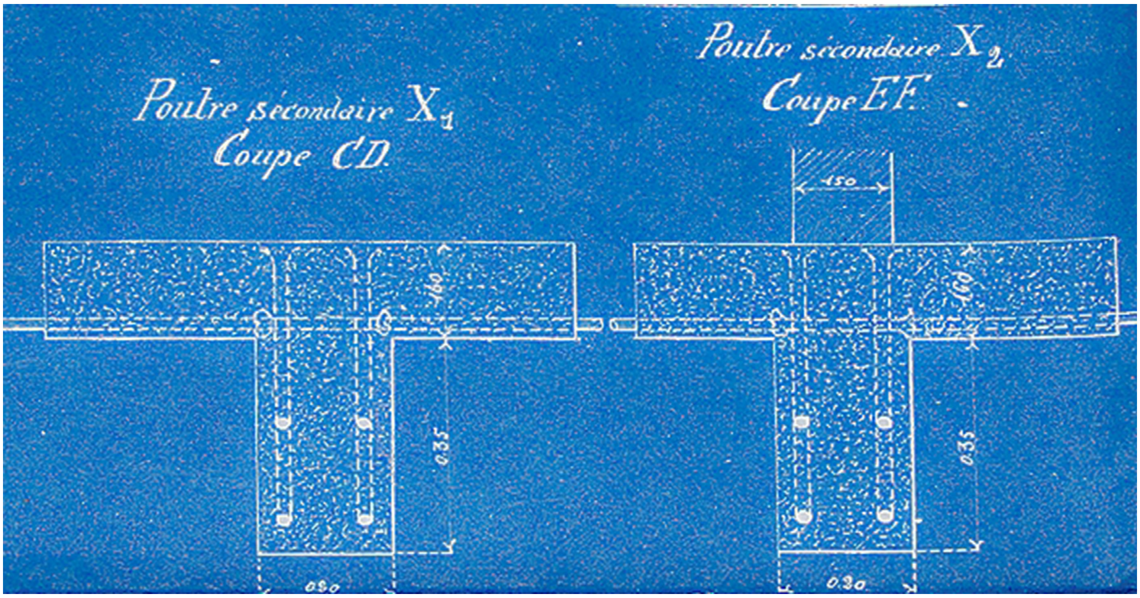

Fig. 5. Detailed position of the stirrups [32].

Fig. 6. Stirrups and upper reinforcement waiting for the slab to be casted, *Villa Figari*, Genoa (1903) [27] – unpublished photo.

2.1. Concrete proportioning

Hennebique never defined a specific mix for concrete. According to [21,26,27], the most common concrete mixes are given as 1 part of cement every 2 parts of sand and 4 parts of gravels (in other cases the formula was 1-3-5, in both cases proportioning in weight) leaving the contractors considerable freedom to change the proportioning [7]. No grading curve nor provision on the

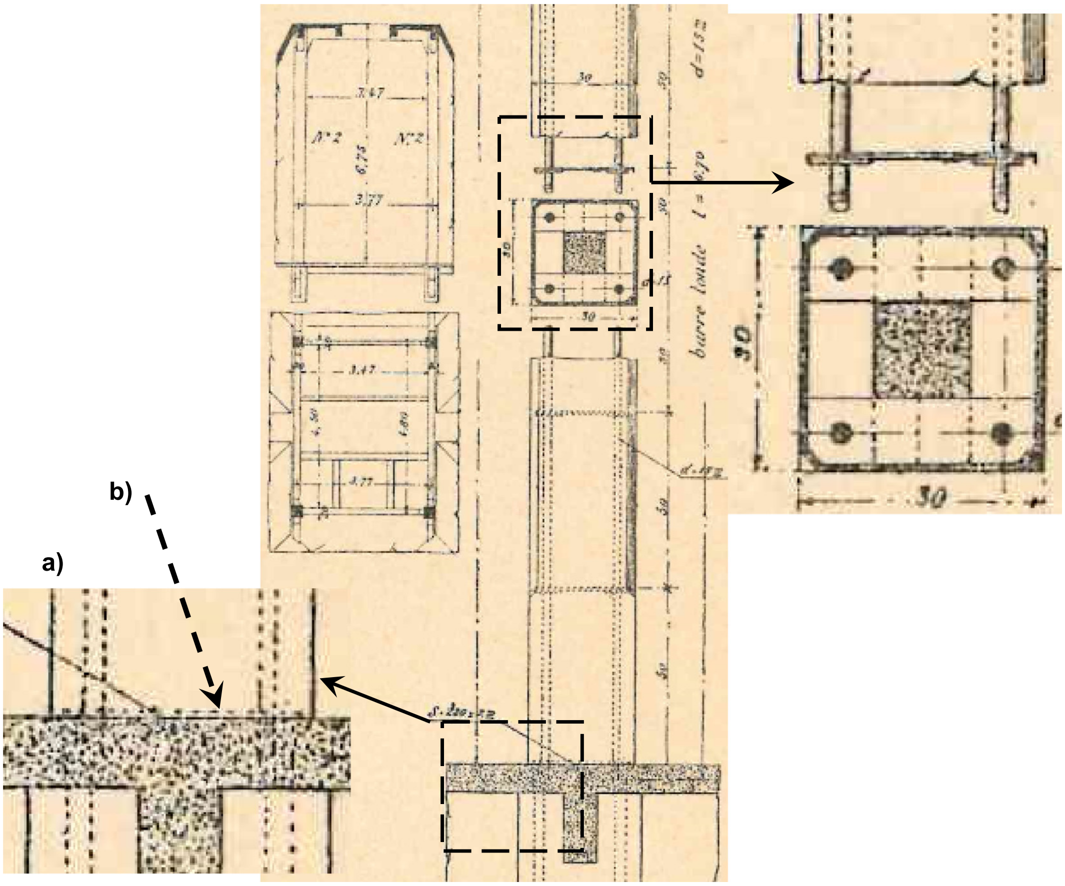

Fig. 7. Longitudinal bars in columns according to [15]. Longitudinal bars are clearly misaligned between adjacent storeys (detail a); the upper bars are connected by means of a large flat stirrup that could prevent connecting the reinforcement of the two storeys.

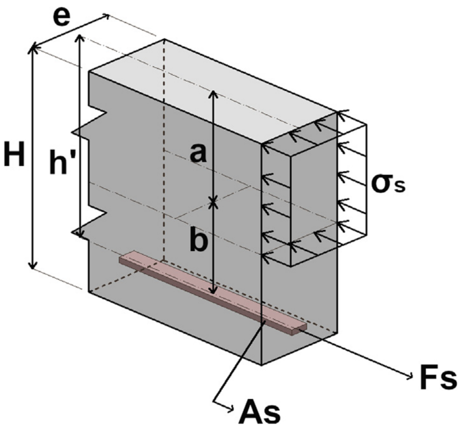

Fig. 8. Geometric quantities for the bended section.

aggregate quality was given, so that the size of the aggregates differed from case to case according to the local availability; besides, in several cases also sand and gravels severely polluted by earth had been used, such as in the case of the Zum Baren Hotel in Basel [28].

The standard cement quantity was 300 kg/m^3 that could be decreased to 250 kg/m^3 in case mechanical mixers were available and could be increased to 500 kg/m^3 for the severely loaded structures and industrial facilities; such a proportioning was rather common in that period [29]. No provision was given about water, which amount was a function of the workability required in the building site. According to the available data base, the water/cement ratio used to range in-between 0.4 and 0.9; it is easy to imagine the resulting large variety of concretes that originates from such an approach.

The mix proportioning was different also according to the structural element to be casted, as opposed to the modern approach; in [7] the concrete of a bridge, which was considered a very important structure also in those times, was found with an average compressive strength of 20 MPa for the columns, 35 MPa for the beams and 55 MPa for the slab.

2.2. Reinforcement

Figures 1 to 3 show the typical reinforcement of a Hennebique beam.

– 50% of the longitudinal reinforcement (cylindrical bars from 10 mm to 40 mm in diameter) is bended up at 1/3 of the span, Fig. 1 [7,27], and anchored on the upper side by means of fish-tail expansions. Such a rule is simply geometric and in the archives there is no rational reason for such a choice; the upper bars, therefore, are not proportioned to the negative bending moment Figs. 1–3.

- the anchorage of the main bars consists of fish-tail ends; hooks were used for secondary bars only, Fig. 2. The fish tails were open as much as to get to twice diameter of the bar. Amongst the large number of load tests to collapse performed by Hennebique and his concessionaries, some showed the collapse of the anchorage of the longitudinal bars, Fig. 3; there is no evidence that this outcome of the test neither led to some change in the detailing of the bars nor raised attention on the bar anchorage.

- The shear reinforcement consists of steel plates, 2-to-3 mm thick, 20-to-50 mm wide, Figs. 4 and 5. The spacing of the stirrups,

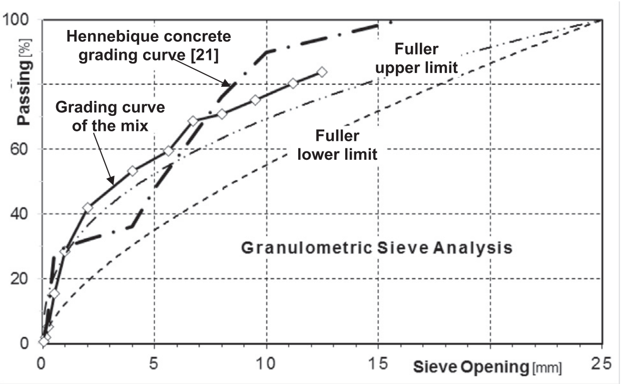

Fig. 9. Granulometric sieve curve of the historical-like concrete used compared with the limit Fuller curves.

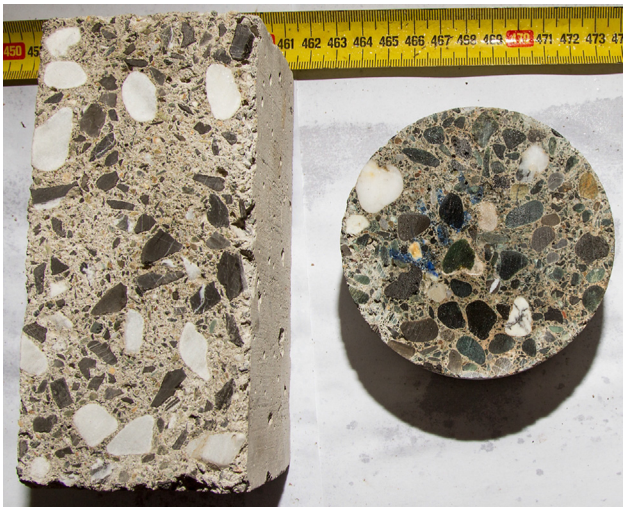

Fig. 10. Cross sections of: a) concrete produced for this research; b) a core extracted from a structure built by *Porcheddu Building Company* (residential building in the park of *Villa Grüber*, Genoa (Italy), 1920–1930 approx.).

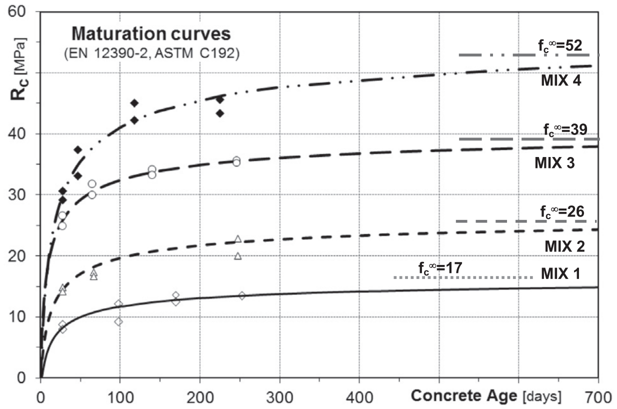

Fig. 11. Maturation curves for the five ancient-type concretes. Curing conditions according to ASTM C192 and EN 12390–2:2019. Estimate of the asymptotic strength.

Fig. 12. Fish-tailed anchorage of bending reinforcement. From a residential building in Genoa, *Villa Grüber* park, Genoa, *Porcheddu Building Company*, in-between 1920-to-1930. Main geometric dimensions.

Fig. 1, was geometrical with minimum spacing close to the supports. There's no explicit origin of such a choice, that is somehow rational and probably originates from the load tests that had been performed. The anchorage of the stirrups is obtained by means of a slight bend of the plate in the compressed part of the beam, Figs. 5 and 6. Also in this case the efficiency of such an anchorage system is to be discussed.

2.3. Detailing

Camillo Guidi (1853-1941), professor of Structural Mechanics at the Technical University of Turin, activated the first academic courses (1899/1900) on reinforced concrete, thus introducing in Italy the new building technology based, at the beginning, on the Hennebique system. In the Appendix to his treatise on Structural Mechanics [15], discussing r.c. columns, he suggests that the longitudinal bars of the columns of a storey should be connected at the base by a large steel plate acting either as a stirrup and as a load distributing device on the lower slab, Fig. 7. Similar stirrups have been found in the Colo-Hughes viaduct in Belgium when it has been demolished [4]. This suggests that there could be no continuity of the longitudinal bars in columns from one storey to the other, which is a crucial issue when discussing the performance to horizontal actions.

The structural scheme used for the beams was always the simply supported beam only. Christophe [26] reports that the maximum bending moment in the middle of the span was assumed as $pl^2/8$ for the main beams, and $pl^2/10$ for secondary beams and slabs, being p the unit load. For simply supported square slabs with reinforcement in both the directions the maximum moment was assumed as large as $pl^2/32$ [28], which is half the value calculated by Structural Mechanics. These design standards could suggest some concern on the amount of reinforcement that we can find in the existing Hennebique structures. In practice, due to conserva-

Table 1
Concrete strength and mixtures for the 5 ancient-type concrete.

Concrete mix	Cement [kN/m^3]	Cement /batch [kg]	Water/Cement ratio	Porosity [%]	$R_{c,28days}$ Cubic strength	C.o.V. [%] (6 samples)
Mix_1	2.0	18.2	1.0	8.3	8.4	3.2
Mix_2	3.0	27.3	0.8	8.6	14.5	2.2
Mix_3	4.2	38.3	0.6	8.3	25.8	2.8
Mix_4	5.0	45.5	0.5	7.3	29.9	0.5
Mix_5	3.0	27.3	0.8	8.3	20.2	3.0

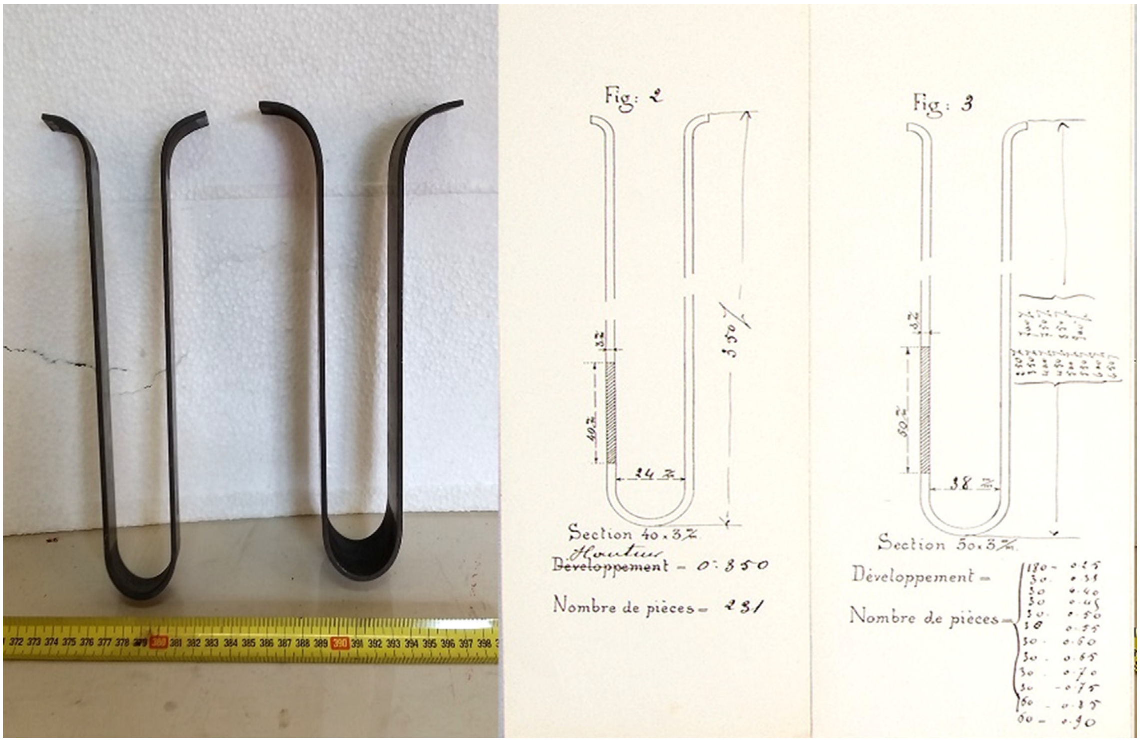

Fig. 13. Plate stirrups – Porcheddu Archive, Technical University of Turin – unpublished drawings.

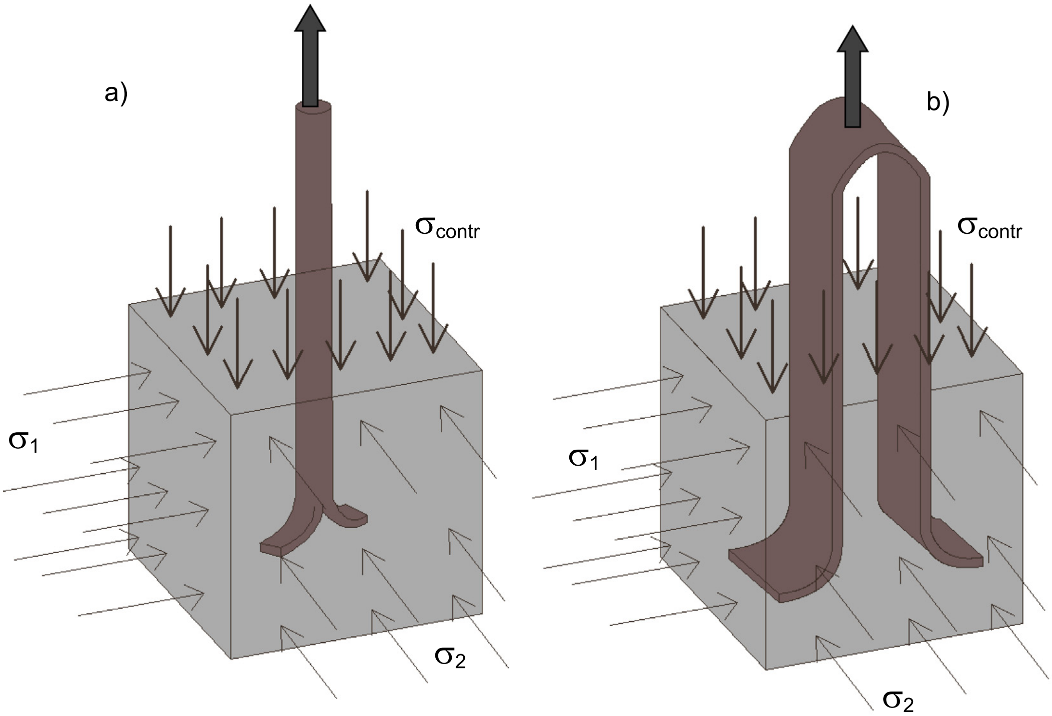

Fig. 14. Tested specimens casted in the concrete cube 150x150x150mm.

tive design formulas and very low allowable stresses, Hennebique structures are almost never under-reinforced for positive bending moments while the negative bending moment is almost always under-reinforced. Besides, the compressed part of the section might be too narrow close to the supports, i.e., in the sections with maximum negative moment.

3. Design formulas

3.1. Bending

Hennebique was aware that in a simply supported beam, the upper part of the section is compressed and the reinforcement is

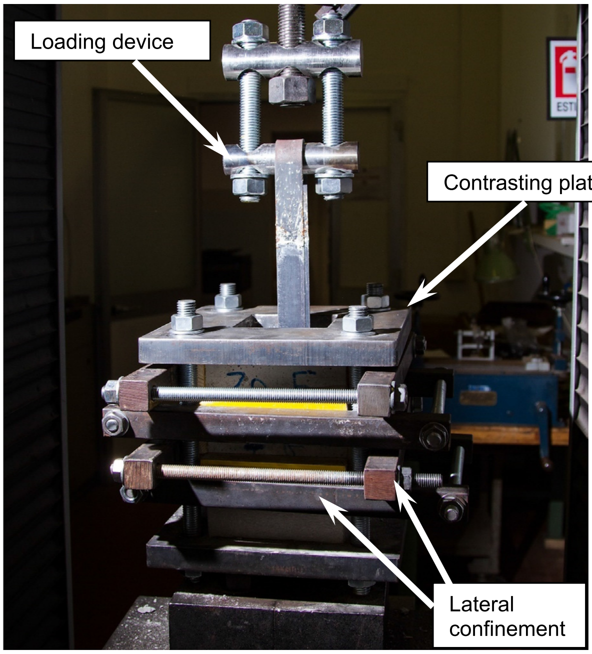

Fig. 15. Experimental setup (for a plate stirrup).

in traction, but the design criteria were somehow creative: half of the moment was "given" to the compressed concrete and the other half to the tensile reinforcement, Eqs. (1) and (2) Fig. 8. The position of the neutral axis did not originate from the equilibrium in the longitudinal direction but setting *a priori* the stresses in the material.

$$M/2 = \sigma_c A_c a/2 = \sigma_c e a^2/2 \quad \text{in compressed concrete} \tag{1}$$

$$M/2 = \sigma_s A_s b \text{ for tensile reinforcement} \tag{2}$$

being the bending moment M in Eqs. (1) and (2) a calculated quantity (see previous section), being the geometry of the beam defined according to some pre-dimensioning criteria, if we set σ_c = 2.5 MPa in Eq. (1) we get the neutral axis position a; setting σ_s = 100 MPa the amount of reinforcement A_s is obtained from Eq. (2).

If we apply Eqs. (1) and (2) to the standard sections of the beams of a residential building, we can observe that the stresses in the materials, assumed *a priori* by Hennebique, are easily exceeded, rising up to 4 MPa for concrete and to 160 MPa for the reinforcement. Since such stresses are far below the strength of the two materials, no problem has ever been found for the existing Hennebique buildings.

3.2. Shear

The way shear reinforcement was calculated reveal a "really very simple" idea of shear: the maximum shear (close to the supports for a simply supported beam) was simply distributed amongst the stirrups assuming a reduced stress in the steel plates of 70 N/mm^2, Eq. (3). No resisting mechanism is assumed and the stirrups are considered as hangers holding the shear force.

$$V = A_s \sigma_{s,s} \cdot n_s \cdot n_b \tag{3}$$

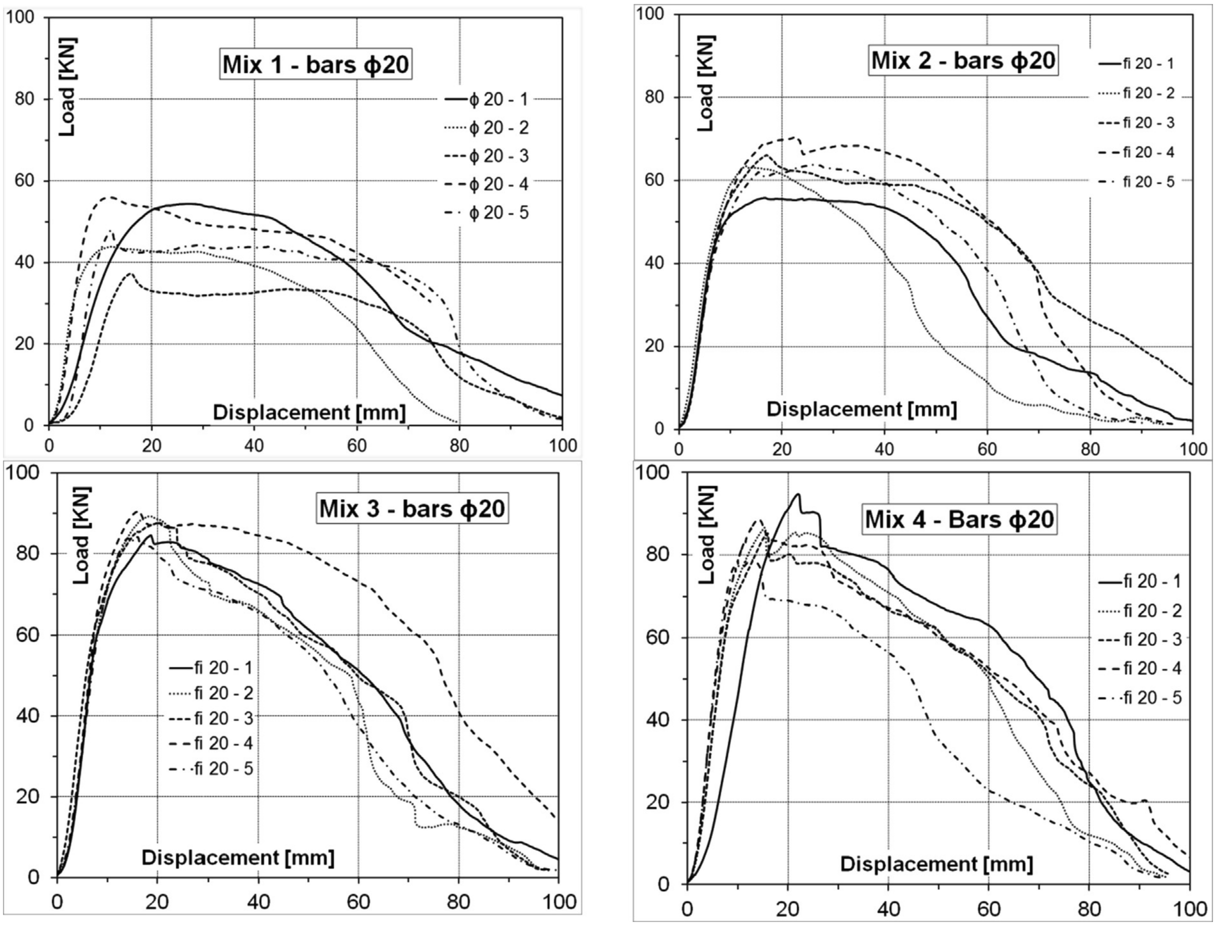

Fig. 16. Load-Displacement response of fish-tailed bars (ϕ = 20 mm).

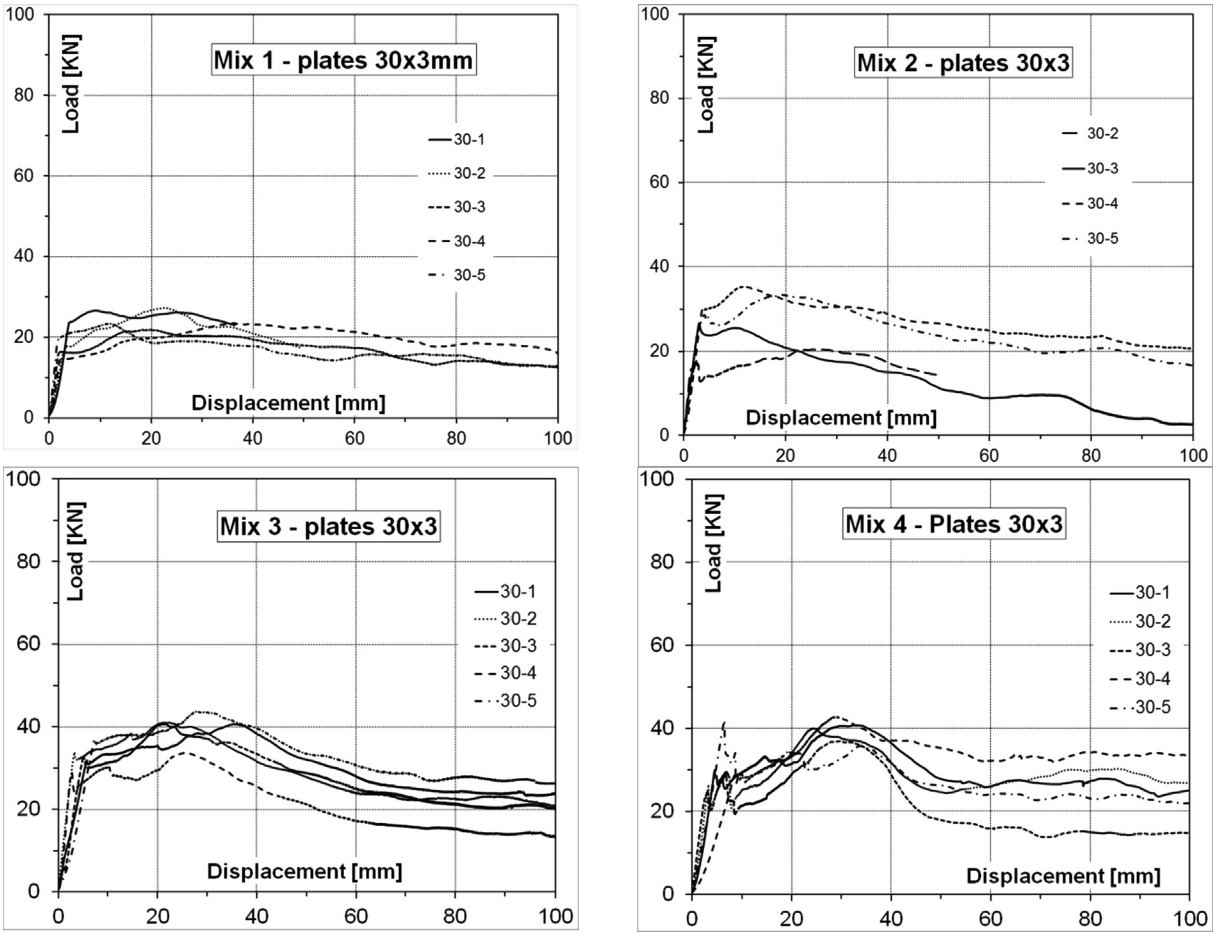

Fig. 17. Load-Displacement response of 30 mm wide plate stirrups.

being $\sigma_{s,s} = 70\ N/mm^2$ the allowable stress in the stirrups defined *a priori*, n_s the number of stirrups in the section and n_b (usually 2) the number of arms/stirrup.

Since Eq. (3) does not take into account the spacing of the stirrups, this was defined according to a geometric progression of unknown origins.

Such a design procedure was called, in those times, the "empirical method", to distinguish it from the analytical procedure called "elastic method". All the unknown settings of the Hennebique system probably originate from the large number of tests performed by the Hennebique company and his concessionaries. Nevertheless, being the system patented, nothing of those tests and of their outcomes has ever been published and the previous statement is just a reasonable hypothesis.

4. The experimental program

The goals of the research are the identification of the anchorage mechanisms up to collapse, either for longitudinal bars (bending) and for stirrups (shear), taking into account different concrete compressive strength and a grading curve that resembles an ancient pre-code concrete.

4.1. Concrete mixtures

An historical concrete may differ from modern concretes because of: i) improper mixture (not following any grading curve); ii) round aggregates; iii) excess in water content; iv) low strength (in general, mainly for residential buildings. Industrial facilities and bridges usually exhibit medium-to-high strength concrete).

The concrete mixture used was defined according to a weight criterion, like the standard building practice in the past: 50 kg of round coarse aggregate (max $\phi = 30$ mm) + 50 kg of crashed medium aggregates (max $\phi = 15$ mm) + 25 kg of crashed fine aggregates (max $\phi = 3$ mm) + 25 kg of sand (max $\phi = 0.5$ mm). Fig. 9 shows the granulometric Fuller sieve curve [33] for the aggregates used and the grading curve deduced for a Hennebique concrete obtained in [21]; it can be seen that pre-code concretes, and the one used in the tests, exhibit grading curves above the upper Fuller curve, nowadays used for aggregate proportioning. Fig. 10 shows two sections: the rectangle has been obtained from the concrete produced for this research, the round section is obtained from a core in an Hennebique structure (residential villa in Genoa, park of *Villa Grüber*, Porcheddu Building Company).

Five concrete types were used, Table 1, aiming at setting a mix that includes the main defects of historical concrete, such as high porosity and severe bleeding. The first four types, for which in Fig. 11 the maturation curves are represented (either EC2 curves [34] and the best-fitting ones, curing conditions of the specimens as in [35–36]), were used for estimating the strength of the anchorage, whilst the fifth concrete was used for estimating the effect of transversal confinement on the anchorage strength.

4.2. Specimens and loading conditions

Two steel specimens have been tested (S275 modern steel used):

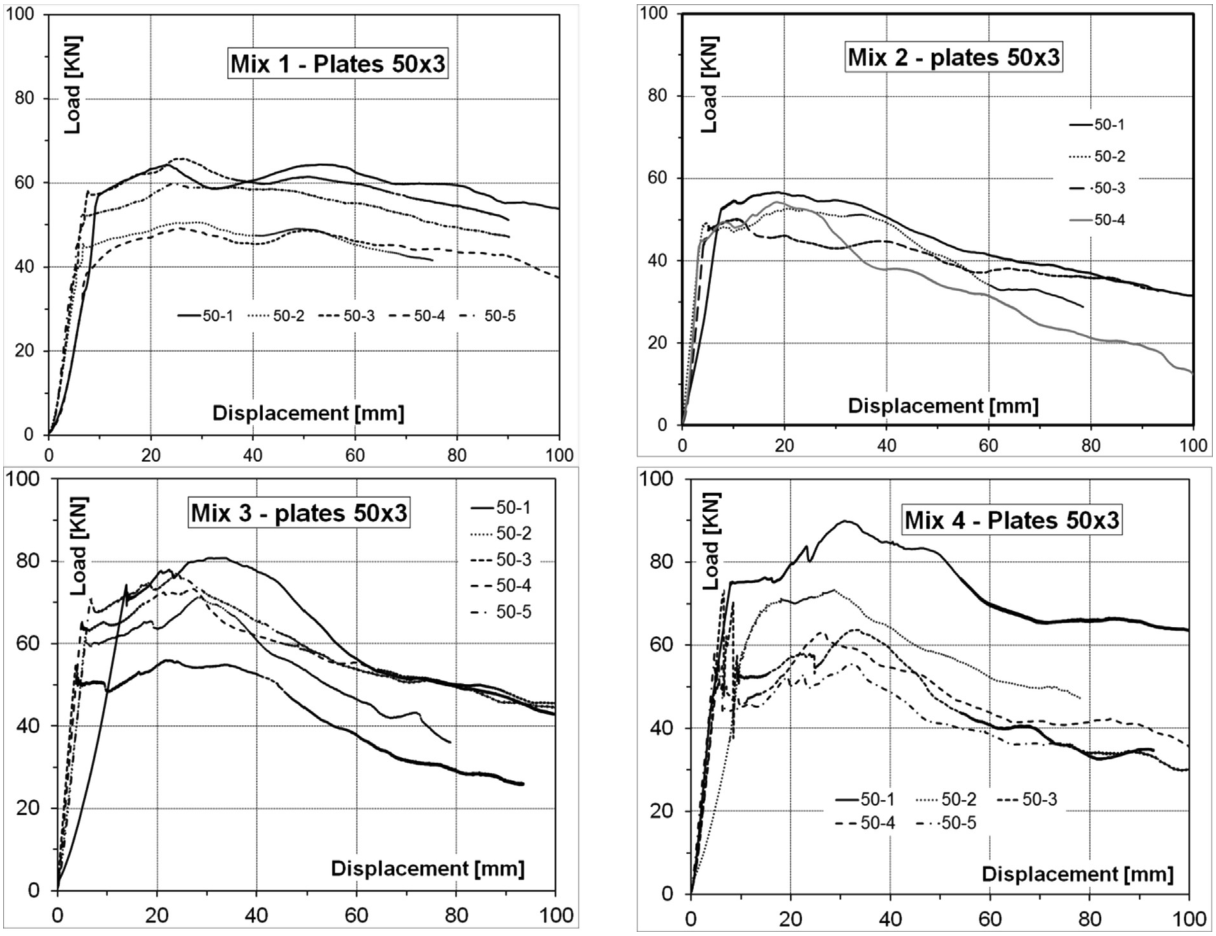

Fig. 18. Load-Displacement response of <u>50 mm wide</u> plate stirrups.

- fish-tailed bars, 20 mm in diameter, Figs. 2 and 12
- plate stirrups 30 and 50 mm wide, 3 mm thick, shaped as the standard stirrups of the Hennebique system, Fig. 13.

The specimens were casted inside concrete cubes 150x150x150mm, Fig. 14, leaving a 20 mm bottom cover to the specimen, i.e., setting the lowest part of the anchorage (fish-tail ends for the bars or bended parts of the stirrups) 20 mm from the bottom of the cube. For both the anchorage systems the four concrete types of Table 1 were used with standard curing conditions ([35,36]).

The load test was displacement-controlled in order to get also the post-peak response of the anchorage. The load was measured by means of a CLASS 1 load cell (error less then 0.1%) and the displacement by means of digital transducers with an error less than 0.01 mm. The loading rate was 3 mm/minute so that the peak load was reached, on the average, after 3 min.

Some remark on the test setup of Figs. 14 and 15 is worth discussion.

i) In general, the pull out force of a bar depends either on its anchorage length, that activates the bond properties of the concrete/reinforcement interface, and on the end shape of the reinforcement. In Hennebique-type structures the anchorage length of the bar is usually limited to 10-to-20 cm; such a limited anchorage length is either very similar to the specimens of Fig. 14 and of limited anchoring efficiency being the reinforcing bars smooth. To this aim, we should note that the early examples of corrugated bars were of very rare use.

ii) The bond-slip relationship for modern corrugated steel bars is measured by means of different setups making use either of prisms and of four-point-loaded beams [37,38]. Since the goal of this research is estimating the contribution of the deformed ends to the anchorage of the reinforcement, the setup of this campaign inserted the deformed ends in the prisms suggested in [37]. Other testing setups, such as the four-point-loaded beam, were unfit to the aim of the research.

The lateral confinement was provided by means of bolts and stiff distributing steel devices, Fig. 15, which applied a lateral average compressive stress σ_1 and σ_2 of 0.75 N/mm^2. This value has to be considered as an average confining stress since the pull-out of the bars, and also of the stirrups, to a much minor extent, activates a non uniform dilatant behaviour of the concrete cube that may change locally the value of the confining stresses.

5. Test outcomes

5.1. Tests results

Fig. 16-to-18 show the load–displacement response of the three different specimens for the four concrete types tested. Fig. 19 summarizes the same diagrams plotting the average load–displacement curve, i.e., plotting a curve that is the average out of the 5 diagrams of the previous figure. Tables 2–4 show the values of the main points of the load–displacement diagrams.

Apart from the anchorage force, a difference is clear between the collapse of the fish-tail end and the plate stirrups: in the first case the peak load is attained at the end of a substantially linear phase and is followed by a relatively fast decrease in strength. In

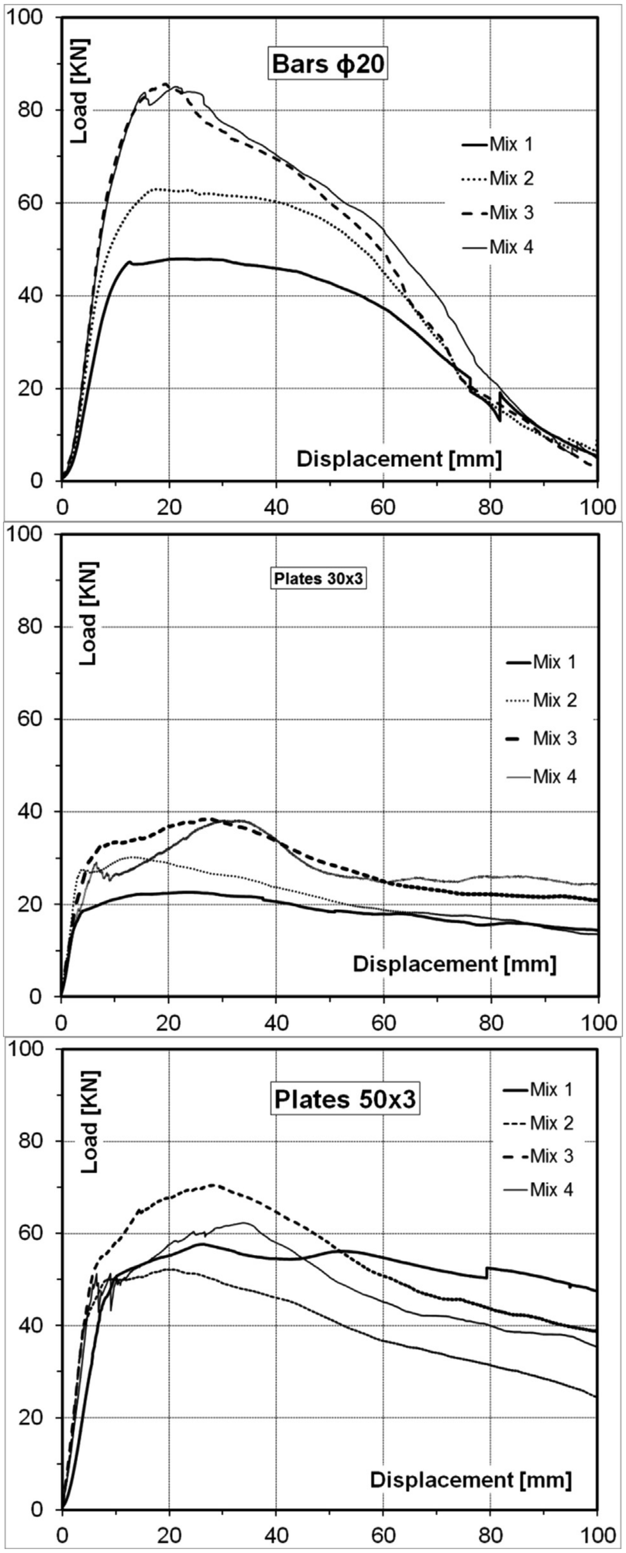

Fig. 19. Load-Displacement response – average values.

the case of stirrups, instead, the post peak response shows a substantially constant anchorage force also for large displacements.

We can also outline that the anchorage strength never induces in the bar a stress level close to yielding. This means that due to anchorage weakness, the steel elements used in the Hennebique System are unable of using their whole section.

5.2. Collapse mechnanism of the anchorage

Fig. 20 shows the fish-tail anchorage before (left) and after (right) the pull out test. It can be recognized that the fish-tail end has been shrank from twice the bar diameter to the bar diameter for low strength concrete and to 0.75 the bar diameter for high strength concrete.

Fig. 21 shows the concrete cube after the pull-out test of the bar. It is clear that the fish-tails slide inside the cube producing a rather limited crushing zone just around its original position.

Figs. 22 and 23 are related to the plate stirrups. In this case the collapse mechanism of the stirrup consists in the rectification of the bended plates, with almost no crushing of the concrete.

These mechanisms explain the main features of the diagrams of Fig. 19: fish-tail anchorage is shrank inside the concrete, which implies crushing of the concrete around the fish tail; for this reason, the anchorage strength depends on the concrete class and the post peak response shows a clearly softening branch, in the same way as compressed concrete in the post peak branch. At macro level, the same behaviour has been observed in the full scale test of [22,23].

For plate stirrups, instead, the collapse mechanism consists of slipping of the plate, that results in flattening of plates, while the mechanical anchoring plays a minor role; for this reason, the anchorage strength does not strongly depend on concrete strength.

5.3. Effect of transversal confinement

Since a relevant part of the collapse mechanism is that of a frictional sliding, lateral confining stresses may play a relevant role in the strength of the anchorage, mainly for the fish-tail anchorage. The previous tests, Figs. 16–18, had a double confining stress field $\sigma_1 = \sigma_2 = 0.75\ \mathrm{N/mm^2}$. Fig. 24 shows the load–displacement response of the fish-tail anchorage if only one of the two confining stress fields (set to $0.75\ \mathrm{N/mm^2}$) is present, which resembles the situation of Fig. 3. Since a new mix has been used, i.e., mix 5 of table 1, also the uniform biaxial confinement tests have been repeated for a direct reliable comparison.

Fig. 24 shows that a moderate lateral confinement, as $0.75\ \mathrm{N/mm^2}$, is responsible of a strength increase of approximately 10-to-20% of the value with a uniaxial confinement.

6. Discussion and assessment formulas

A common feature of the collapse mechanisms of the Hennebique-type anchorages is that in both cases the reinforcing bar or the plate stirrup is rectified.

Tables 2–4 show that there is no unique and clear dependence of the anchorage strength on the concrete class. We can say that higher strength in concrete leads to higher strength in the anchorage but this is not true above 25 MPa.

6.1. Bending reinforcement – fish-tailed bars

For the 20 mm bar, the force needed to close the fish-tail end from twice the diameter of the bar to its diameter is to be found in the range 85-to-90kN (the value may change according to the exact section of the fish-tail in which yielding takes place), substantially the maximum strength of the anchorage, Fig. 19, for the highest concrete class.

Considering Fig. 19, we observe that the anchorage strength depends on the force needed to close the fish-tail as represented in Fig. 25: almost linear up to concrete strength of $25\ \mathrm{N/mm^2}$, and constant after that limit. Besides, since lateral confinement of the anchorage may be uniaxial or rather weak, like in the case

Table 2
Tests data for the 20 mm bars.

Cubic strength	R_c = 8.4 N/mm^2				R_c = 14.5 N/mm^2			
ϕ 20 mm bars	F_{el}	$\sigma(F_{el})$	F_u	$\sigma(Fu)$	F_{el}	$\sigma(F_{el})$	F_u	$\sigma(Fu)$
1	50.0	159.2	54.4	173.3	50.0	159.2	55.8	177.7
2	42.0	133.7	43.9	139.6	58.0	184.6	63.5	202.3
3	37.0	117.8	37.3	117.8	55.0	175.1	66.2	210.6
4	48.1	153.1	55.9	178.0	62.0	197.4	70.5	224.3
5	55.0	175.1	48.1	153.2	50.0	159.2	63.7	202.8
Average	*46.4*	*147.8*	*47.9*	*152.5*	*55.0*	*175.1*	*63.9*	*203.5*
Std. Dev. [%]	*15.1*		*16.0*		*9.4*		*8.3*	
Cubic strength	R_c = 25.0 N/mm^2				R_c = 30.0 N/mm^2			
ϕ 20 mm bars	F_{el}	$\sigma(F_{el})$	F_u	$\sigma(Fu)$	F_{el}	$\sigma(F_{el})$	F_u	$\sigma(Fu)$
1	70.0	222.8	84.5	269.0	90.0	286.5	94.7	301.4
2	75.0	238.7	89.2	238.8	80.0	254.6	86.6	275.7
3	75.0	238.7	87.6	278.8	70.0	222.8	85.1	270.9
4	75.0	238.7	90.5	288.1	80.0	254.6	88.6	282.0
5	75.0	238.7	84.1	267.7	76.0	241.9	78.7	250.5
Average	*74.0*	*235.5*	*87.2*	*277.5*	*76.0*	*252.1*	*86.7*	*276.1*
Std. Dev. [%]	*3.0*		*3.2*		*9.2*		*6.7*	

Table 3
Tests data for the 30 mm wide plate stirrups.

Cubic strength	R_c = 8.4 N/mm^2				R_c = 14.5 N/mm^2			
30 mm plates	F_{el}	$\sigma(F_{el})$	F_u	$\sigma(Fu)$	F_{el}	$\sigma(F_{el})$	F_u	$\sigma(Fu)$
1	23.0	127.8	26.6	147.9	29.0	161.1	29.0	161.1
2	28.0	152.0	27.4	152.0	17.5	97.2	20.6	114.3
3	16.0	121.2	21.8	121.2	26.6	147.8	26.6	147.8
4	14.5	130.8	23.6	130.8	30.0	166.7	35.5	197.2
5	19.4	129.5	23.3	129.5	28.5	158.3	33.4	185.6
Average	*18.2*	*136.3*	*24.5*	*136.3*	*26.3*	*146.2*	*29.0*	*161.2*
Std. Dev. [%]	*18*		*9.6*		*19.3*		*20.3*	
Cubic strength	R_c = 25.0 N/mm^2				R_c = 30.0 N/mm^2			
30 mm plates	F_{el}	$\sigma(F_{el})$	F_u	$\sigma(Fu)$	F_{el}	$\sigma(F_{el})$	F_u	$\sigma(Fu)$
1	31.9	177.2	40.6	225.7	30.0	166.7	40.8	226.7
2	33.9	188.1	41.0	227.9	26.5	147.2	40.0	222.2
3	33.0	183.3	40.8	226.5	25.0	138.9	37.0	205.6
4	29.0	161.1	33.8	187.7	29.1	161.7	42.7	237.2
5	37.2	206.6	43.7	242.9	42.1	234.1	42.1	233.9
Average	*33.0*	*183.3*	*40.0*	*222.2*	*30.5*	*169.7*	*40.5*	*225.1*
Std. Dev. [%]	*9.0*		*9.2*		*22.2*		*5.5*	

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Table 4
Tests data for the 50 mm wide plate stirrups.

Cubic strength	R_c = 8.4 N/mm^2				R_c = 14.5 N/mm^2			
50 mm plates	F_{el}	$\sigma(F_{el})$	F_u	$\sigma(Fu)$	F_{el}	$\sigma(F_{el})$	F_u	$\sigma(Fu)$
1	57.0	190.0	64.4	214.6	52.0	173.3	55.7	185.5
2	45.0	150.0	50.6	168.5	48.0	160.0	52.8	175.8
3	57.0	190.0	65.7	219.1	48.0	160.0	50.2	167.4
4	38.5	128.3	49.2	163.8	48.0	160.0	54.3	180.9
5	52.0	173.3	59.8	199.4	42.0	140.0	58.5	195.0
Average	*49.9*	*166.3*	*57.9*	*193.1*	*47.6*	*158.7*	*54.3*	*180.9*
Std. Dev. [%]	*16.1*		*13.3*		*7.5*		*5.7*	
Cubic strength	R_c = 25.0 N/mm^2				R_c = 30.0 N/mm^2			
50 mm plates	F_{el}	$\sigma(F_{el})$	F_u	$\sigma(Fu)$	F_{el}	$\sigma(F_{el})$	F_u	$\sigma(Fu)$
1	73.4	244.7	80.8	269.3	74.4	248.0	74.4	248.0
2	61.8	206.0	71.2	237.4	60.0	200.0	73.4	244.7
3	55.9	186.3	56.0	186.7	73.5	245.0	43.5	245.0
4	66.0	220.0	73.3	244.3	56.9	189.7	63.2	210.7
5	71.0	236.7	77.1	257.0	58.1	193.7	58.1	193.7
Average	*65.6*	*218.7*	*71.8*	*238.9*	*64.6*	*215.3*	*67.1*	*223.5*
Std. Dev. [%]	*10.7*		*13.3*		*13.41*		*11.5*	

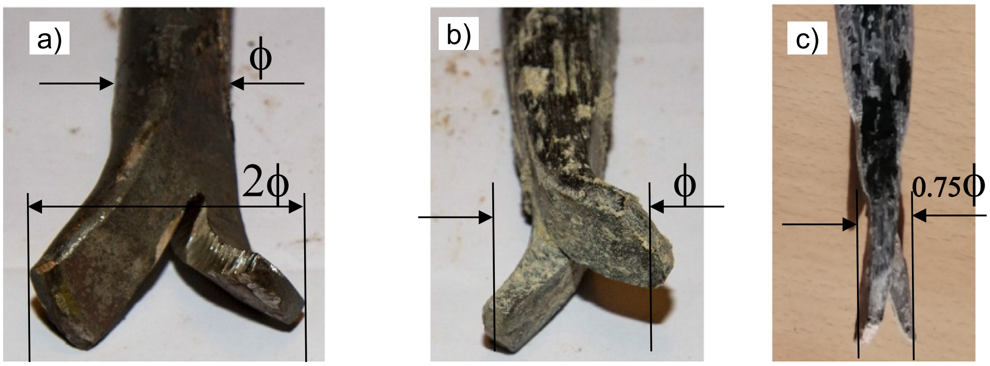

Fig. 20. Fish-tail anchorage a) before and after the pull out test for b) low strength and c) high strength concrete.

Fig. 21. Track left in the concrete cube by the fish-tail anchorage. a) sliding of the bar along the steel/concrete interface; b) the central track (black arrows) show the sliding and the side crushing of the concrete due to the two tails.

Fig. 22. Plate stirrup: deformed stirrup after the pull-out test.

of Fig. 3, the outcomes of Fig. 24 suggest to reduce the anchorage strength by a factor of 2/3.

To set a design formula for the anchorage strength $F_{anchorage}$ as a function of the fish-tail closure force $F_{closure}$ we need to take into account the effect of lateral confinement, Fig. 24, a safety coefficient γ_c for concrete that should guarantee the anchorage to remain in the linear phase, i.e. before any sliding takes place, thus obtaining:

$$\begin{aligned} F_{anchorage} &= 2/3\ F_{closure}(0.275 + 0.625 f_c/f_{c0})\ /\gamma_c \\ &= (0.183 + 0.417 f_c/f_{c0})\ F_{closure}/\gamma_c\ for\ f_c \in [5,25] N/mm^2 \end{aligned}$$

$$F_{anchorage} = 0.60\ *\ F_{closure}/\gamma_c\ for\ f_c > 25\ N/mm^2$$

where f_{c0} = 25 N/mm^2; $F_{closure}$ is the force needed to close from twice the diameter of the bar to the diameter itself the fish tails, that should be better either estimated theoretically and

Fig. 23. Track left in the concrete cube by the plate stirrup. It is clear that almost no concrete crushing takes place around the stirrup.

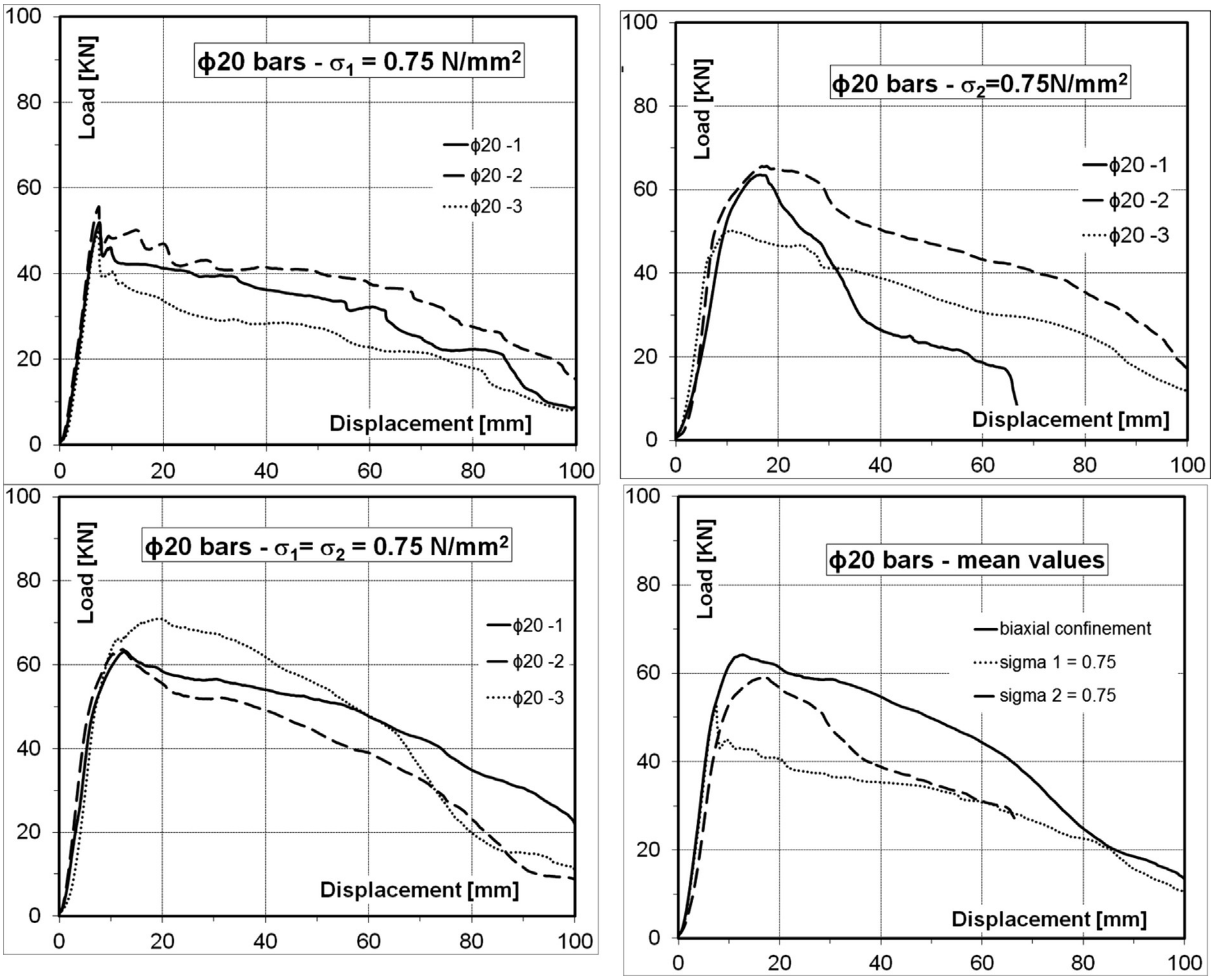

Fig. 24. Load-Displacement response of the 20 mm bar with different transversal confining stresses – concrete mix n. 5.

experimentally measured. γ_c is a safety margin related to the concrete. Since historical concrete is rather different from modern concrete, mainly due to inhomogeneity in the production processes, γ_c should be larger than the usually assumed value of 1.5. It could be obtained from the dispersion of the identification tests; a reference value could be in the range [1.7, 2.0]. Fig. 25 plots Eqs. (4) assuming γ_c = 1, thus fitting the test data.

6.2. Shear reinforcement – Plate stirrups

Figs. 17 and 18 show that: i) the anchorage force depends on the concrete strength; ii) after the peak load is reached, the anchorage strength remains approximately constant. Figs. 21 and 22 show that the collapse mechanism of the anchorage gets two contributions: i) sliding of the steel plate; ii) some damage of the concrete close to the stirrup sharp end (cut section from the steel strip).

The actual details of the collapse mechanism are rather hard to be modelled since the stirrup-concrete interactions involve either normal and tangential stresses, non linear material response either in the concrete and in the steel plate, thus involving plastic work in both the materials and strain hardening in the steel plate. Since the only test data is the extraction force, we cannot provide not even any reasonable assumption for the actual stress and strain distribution in the anchorage. Therefore, a phenomenological approach should be better used.

The parameters involved in the anchorage efficiency are the strength of the materials (steel and concrete) and the geometry of the anchorage; besides, the problem is strongly non linear. Since the plastic work in concrete is related either to crack propagation and to material crushing, to the geometric dimensions of the steel plates (linearly related to the width and with a cubic dependence on the thickness) we can assume as a reference anchorage strength the one measured for the 30 mm wide stirrups $F_{anchorage,0}$ = 40kN.

In the upper part of a bended section the compressive stresses are parallel to the plates of the stirrups. Therefore, they do not provide any confining effect to the anchorage of the stirrups. For this reason, looking to design formulas, we should reduce by 2/3 the strength of the anchorage. In this way we can obtain from a best fitting procedure the following equations:

$$\begin{aligned} F_{anchorage} &= 2/3\ F_{anchorage,0}(f_c/f_{c0})^{0.5}(w/w_0)^{1.1}(t/t_0)^3/\gamma_c = \\ &= 26.7\ (f_c/25)^{0.5}(w/30)^{1.1}(t/3)^3/\gamma_c\ for\ f_c \leqslant 25\ N/mm^2 \end{aligned}$$

$$\begin{aligned} F_{anchorage} &= 2/3\ *\ F_{anchorage,0}(w/w_0)^{1.1}(t/t_0)^3/\gamma_c = \\ &= 26.7\ (w/30)^{1.1}(t/3)^3/\gamma_c\ for\ f_c > 25\ N/mm^2 \end{aligned}$$

where f_{c0} = 25 N/mm^2, is the reference concrete strength, w_0 = 30 mm and t_0 = 3 mm are the width and thickness of the stirrup related to $F_{anchorage,0}$. Fig. 26 plots Eqs. (5) and the test data, neglecting the 2/3 and γ_c safety coefficients to show the fitting of the test data.

Test data for the 50 mm wide stirrups are rather dispersed, so that the R^2 is rather low. If we neglected the unusual tests with 8.4 N/mm^2 concrete, the R^2 value would be as large as 0.94 (in brackets in Fig. 26).

In both the cases, fish-tail ends and plate stirrups, the previous formulas allow the assessment of the anchorage of the reinforcement in Hennebique-type reinforced concrete.

The structural scheme of a continuous beams in the design of Hennebique-type structures is rather rare and is mainly limited to bridges. In Italy, residential buildings had been designed considering the beams as a series of simply supported beams which reinforcement was calculated and shaped span by span. In these cases, the reduced efficiency of the fish-tail ends means that, close to the supports, the reinforcement can be only partially exploited, i.e. less than its whole section. This may affect the shear assessment of the beams close to the columns.

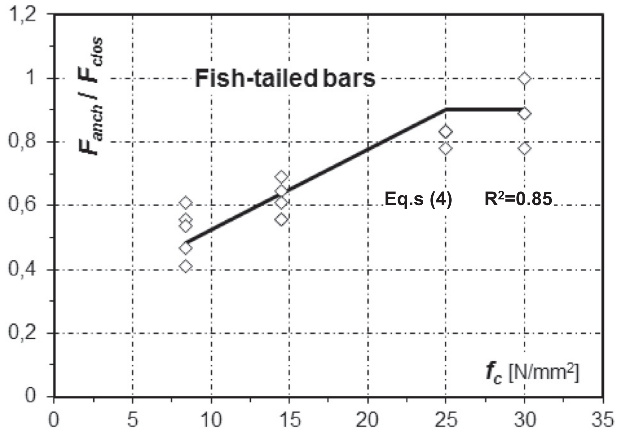

Fig. 25. Anchorage strength (normalized by the closure force) vs. concrete class for 20 mm bars.

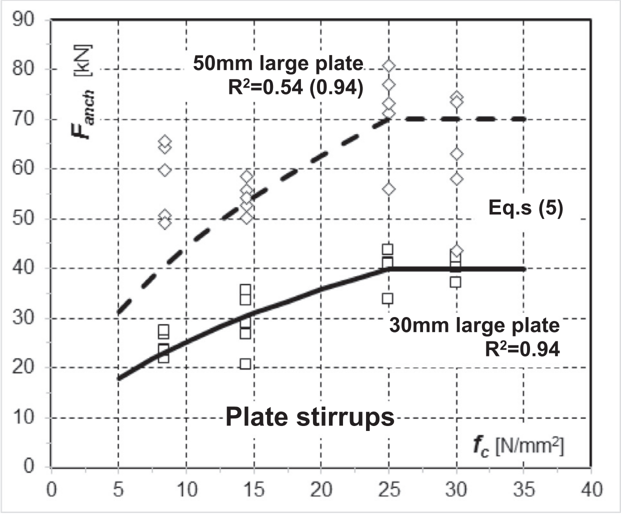

Fig. 26. Anchorage strength vs. concrete class for plate stirrups.

Besides, also the anchorage of the stirrups allows only a partial exploitation of the shear reinforcement.

When the assessment of Hennebique-type structures is needed, besides all the tests needed to characterize the materials and to identify the reinforcement, a further investigation is strongly needed, that is the identification of the actual geometry of the anchorages. Even though the Hennebique system had been patented, it did not remain unchanged in time, so that we are never really sure of the specific choice adopted in a specific case. Besides, several other building companies used his patent legally or simply by an unauthorized copy, such as Ribera in Spain, which makes this issue also more troublesome in several cases.

7. Conclusions

The most widespread reinforced concrete structures in the pre-code era are the Hennebique-type ones, diffused mainly, but not only, in Europe. Due to some specific feature of the Hennebique patent, modern approaches to the assessment of these ancient r.c. structures are not always applicable, such as in the case of anchorage of the longitudinal bars and the shape of the stirrups. In these cases, the shape of the bar (for longitudinal reinforcing) and of the plate ends (for stirrups) provides an anchorage that is not covered by any of the modern codes. Due to a reduced anchorage length of both the types of reinforcements, the assessment of Hennebique-type reinforced concrete structural members would be rather troublesome.

To get more information in the anchorage of Hennebique-type reinforcements, an experimental campaign has been performed on the anchorage of fish-tail ending bars and on plate stirrups, resembling the reinforcement used by Hennebique companies, in ancient-like concrete with different strength.

The outcomes allowed to understand some basic issues on the collapse of the anchorage mechanism, that closes the fish-tails and flattens the plates before the yielding strength of steel is reached. Some code-type formulas have been deduced that may be useful in the assessment of pre-code Hennebique-type reinforced concrete structures.

CRediT authorship contribution statement

Antonio Brencich: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Matteo Nebiacolombo:** Investigation, Resources, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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