



STEEL ANCHORAGES IN BRICK WALLS: TESTS AND SEISMIC DESIGN CRITERIA.

F. BUCCINO and E. VITIELLO

Department of Structural Engineering, Politecnico di Milano,
P.za Leonardo da Vinci 32, 20133 Milan, Italy.

ABSTRACT

Steel tendons, orthogonal to external walls at floor levels, are an efficient mean to prevent collapse of bearing walls subjected to out-of-plane seismic forces. A number of methods to connect these tendons to the walls have been developed, based on engineering skill. However explicit research and design rules are lacking on these important structural details. The object of the paper is to suggest design criteria for such anchorages, based on theoretical model and validated by experimental evidence. Since the design criteria of the steel part of any anchorages are well established, in the present research-work attention has been paid only to the "punching" limit state of the steel anchorage into the brickwall.

Full scale models have been tested. Cyclically varying loadings have been applied as pull-out forces (fig.1) to simulate their seismic behaviour. The geometry of all the brick models has been the same, but different structural properties have been alternatively incorporated into the different models, namely :

- 1) Three alternative shapes of anchorages (steel plate, hook and loop).
- 2) Various level of strength of the mortar in the brickwork.
- 3) Presence or absence of vertical in plane stress, to simulate effects of vertical loads.

The conclusions obtained from the test campaign are the following : the ultimate strength depends very much on the anchorages type, on the quality of the mortar and on the confinement. For certain type of anchorages, even when the applied loads exceed the first yielding of the bricks, quite a few loading cycles are needed to induce degradation of the bearing capacity, and many cycles are needed to reach the total collapse of the connection. The latter involves large displacement of the tendons and of the bricks. Therefore these connections are seen to be "ductile". However hysteresis loops can not develop (since inversion of load in the tendon is not possible) and energy dissipation is low. For other types of anchorages the collapse seem "fragile". In any case the ultimate resistance of the anchorages increase with the size of the portion of brick wall that is mobilized after first yielding of the wall.

The above results suggest evident design criteria. In addition, general design formulas are derived by the authors to predict the strength of the anchorages, taking into account: shape of the anchorage, dimension, quality of the mortar, contemporary in-plane stress in the wall. This formulas fit quite well the tests. In addition they are quite simple and can be easily incorporated into a code of practice.

Key-words : brickwalls, anchorages, retrofitting connections.

INTRODUCTION

During an earthquake inertia forces, acting orthogonally to external walls, may produce collapse due to loss of equilibrium (fig.1). It is important to provide wall/floor connections, that may resist the out-ward forces. In this case stresses on the wall reduces to bending and shear, as outlined in fig.2. Design and checks for bending and shear in a brickwall is not a problem, and common codes can be used in practice (see, for instance, ref.1). Design of slab-wall connections is often an easy task for new buildings, where a reinforced concrete continuous rib may be cast into the wall (fig.3). In the seismic retrofitting of existing buildings one should design steel tendons ending in steel rods or plates as anchorages with the walls (typically if the floor structure is made of timber, fig.4). Instead, if floors are rebuilt using reinforced concrete, connections with existing wall may be easily achieved by the insertion reinforcing bars (loops or hooks) into the core of the brickwall, see fig.5. In both the situations of fig.4 and 5 the strenght of the connections is basically due to the resistance of the wall to a "punching" effect of the anchorage. This effect needs experimental investigation and rules for design, that are the objects of the present paper.

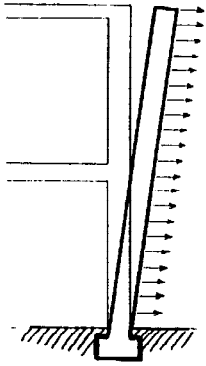


Fig. 1 Collapse mode for out-of-plane inertia forces of an external bearing wall poorly connected at floor level.

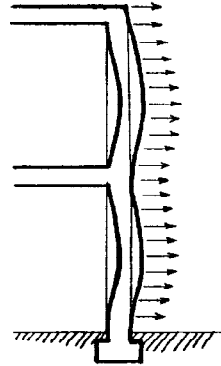


Fig. 2 Schematic behaviour under seismic loads of a wall well connected to floors.

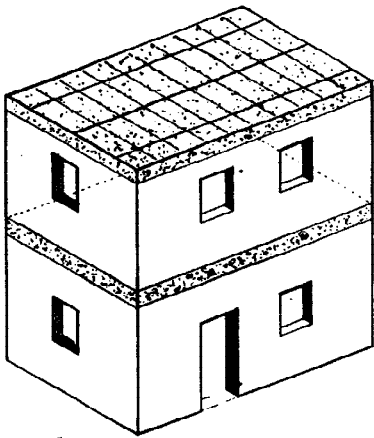


Fig.3 Wall-slab connections with a continuous (reinforced concrete) rib.

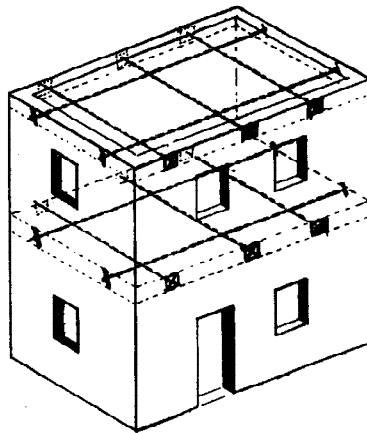


Fig. 4 Tendons inside timber floors, connected to external walls by various type of anchorages.

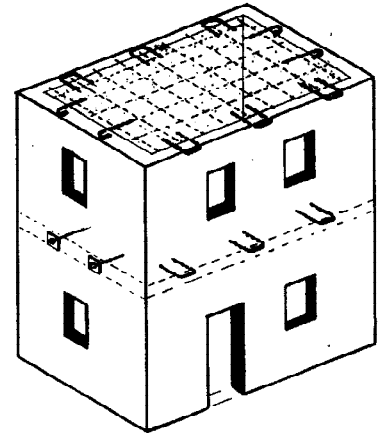


Fig. 5 Wall-slab connections with reinforcing bars, tied to brickwork.

CHARACTERISTICS OF THE MODELS AND TEST PROCEDURE

A total of 16 models of wall were tested, all with the same external geometry : a masonry pannel of 70 x 70 cm, 23 cm thick. Around each model a light steel frame was set (for casting and transportation), but it was released during loading, in such a way to simulate an in-plane unconstrained loading condition. In the center of each model an anchorage (type A, or type B, or type C, see the following figures) was cast with a rod of steel tendon emerging from the apposite side of the model. Loads were applied monotonically to the tendon, up to the first yielding (load level = F_{max}). Then, cycles of loads were repeated, always reaching the new (may be lower) yielding level, untill very large displacements were reached (load level = F_u). In the case of four models (see last chapter) a vertical force P was applied and kept constant during all the loading program, to simulate vertical dead loads on the brickwall.

All the models were built using plain clay bricks, size 5 x 11 x 23 cm, of rather high strength (around 47 MPa, compression test). Two different type of mortar were used, corresponding to a good quality of standard mortar (M5) and a poor quality of mortar (M1), according to the classification of ref. 1. In order to characterize the strength of the masonry a series of tests were performed on prisms of brickwork, cut out from the tested models. The tests on these specimens were aimed primarily to assess the real resistance in shear along the mortar layers. Table 1 summarize the test results on these specimens.

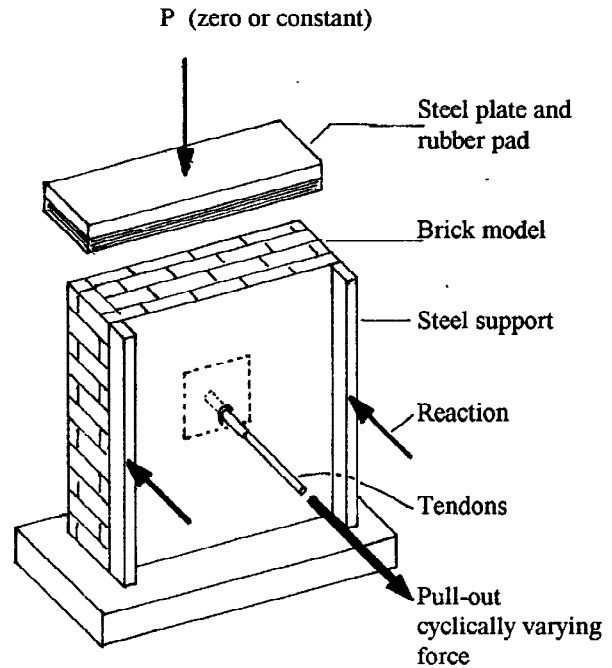
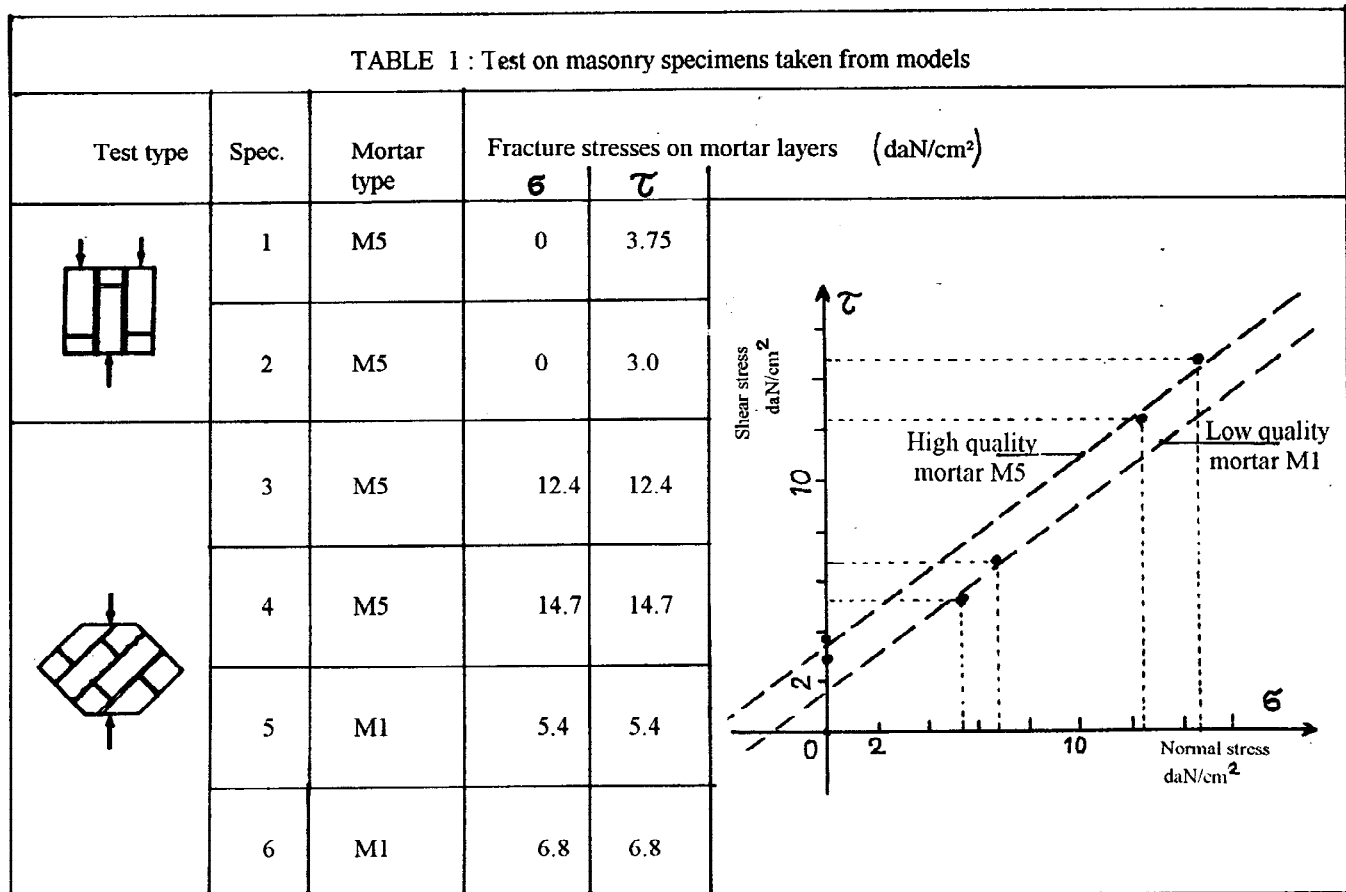


Fig.6 Scheme of loading test.



RESULTS OF ANCHORAGES TYPE A

This is the simplest connection, where a hook shaped reinforcing bar is inserted in a pocket of the wall, grouted with common concrete. In our case the hook and the bar size were designed such that the bond between concrete and steel and the strength in tension of the bar are not critical. The failure mode that was evident during tests is due to a failure of bond between concrete and bricks and a sliding of the concrete block outside the wall. This is shown in fig. 7 and 8.



Fig. 8 Picture of anchorage type A at collapse.

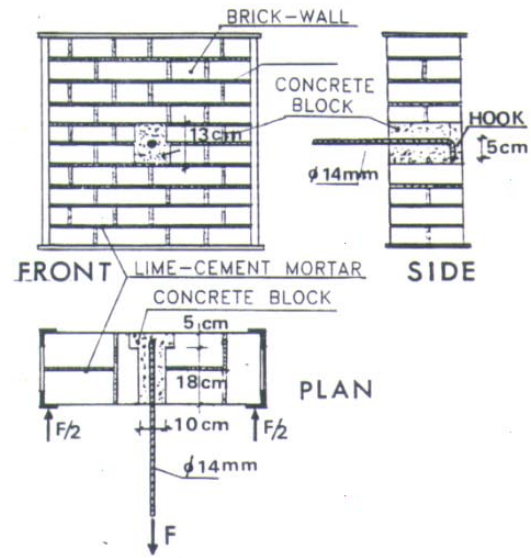


TABLE 2 : Anchorages type A - Results, $P = 0$
(Units : daN)

Model -Mortar	F max	F u
A1 - M5	3200	2800
A2 - M5	3200	3000
A3 - M5	3600	3400
A1 - M1	2000	1900
A2 - M1	2000	1800

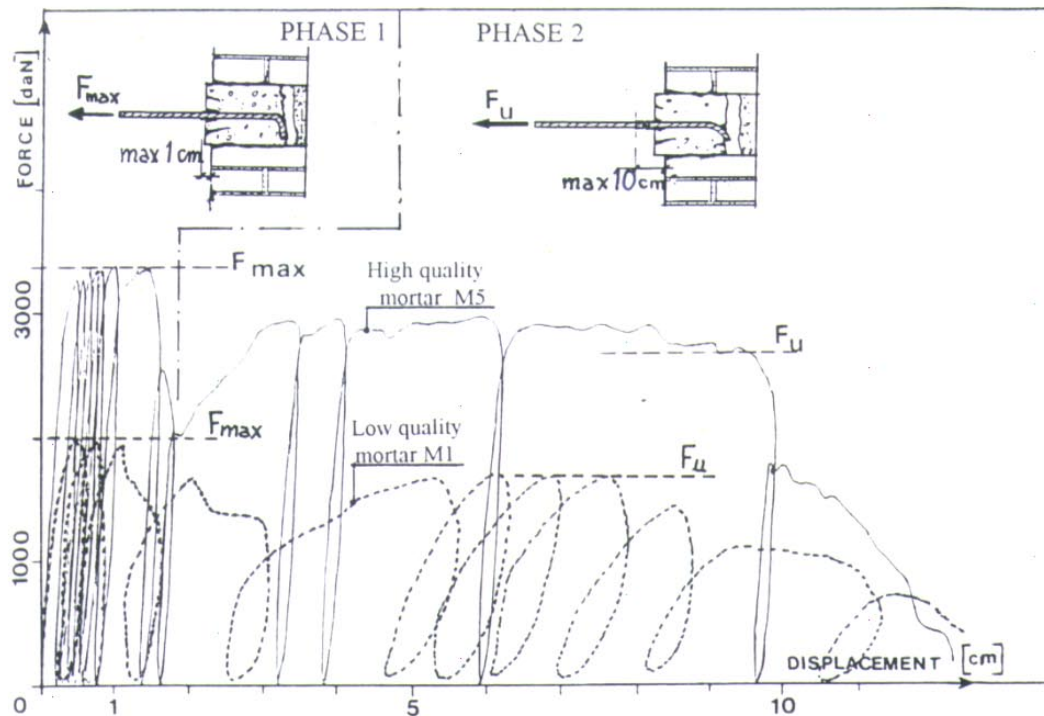


Fig. 7 Anchorage type A. Force-displacement diagram for cyclic loads.

Phase 1 : Cracks develop into concrete and between concrete and bricks.

Phase 2 : The block of concrete slides outside . Friction resists on lateral surface.

RESULTS OF ANCHORAGES TYPE B

This is a rather common and inexpensive way of connecting new r.c. slab to existing brick wall : holes are drilled into the wall and reinf. bars make a loop around small portions of bricks. In our models the size of the bar is large enough to avoid failure in tension. A failure mode, similar to the previous case A, is here obtained. A block of material is extracted from the wall and it contains the bricks inside the loop too, see fig. 9 and 10.

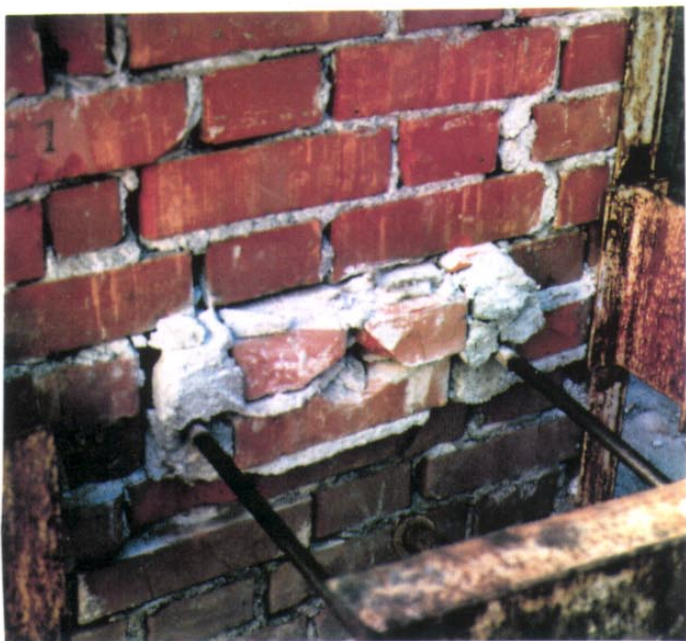


Fig. 9 Picture of anchorage type B at collapse.

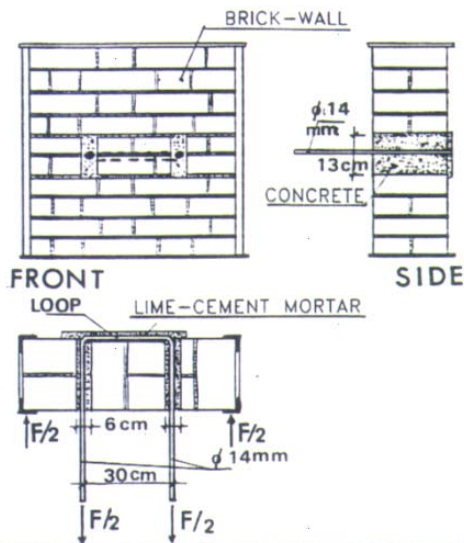


TABLE 3 : Anchorage type B - Results , P = 0
(Units : daN)

Model-Mortar	F max	F _u
B1 - M5	7500	4700
B2 - M5	7500	4700
B1 - M1	2800	2000
B2 - M1	3700	2000

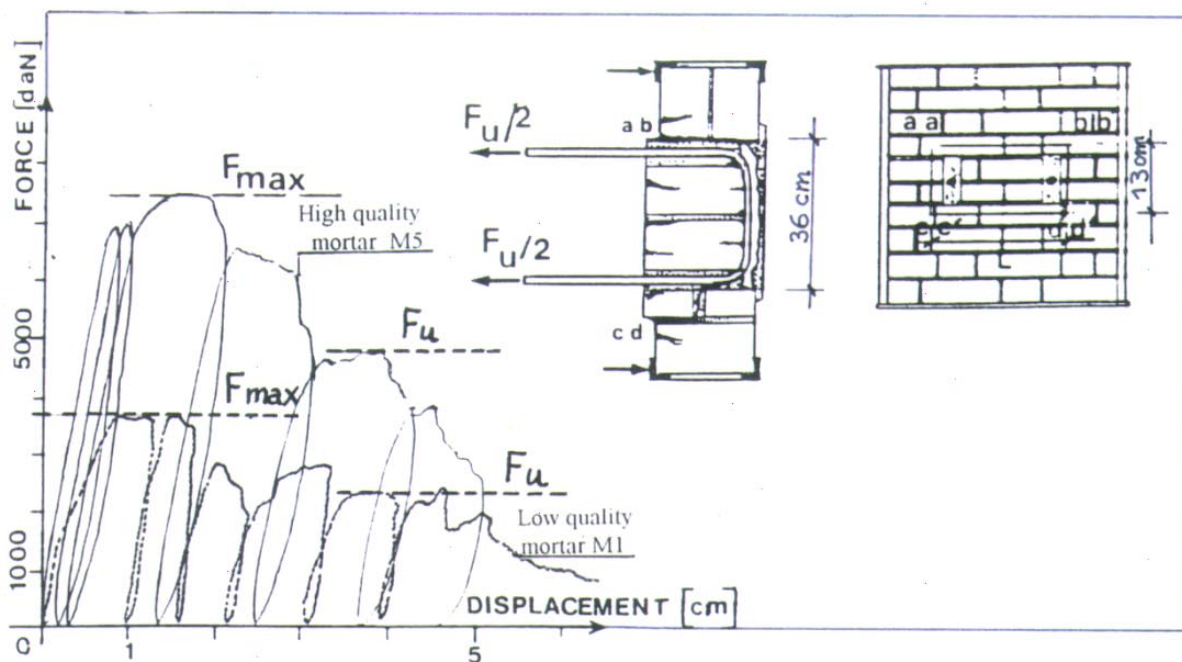


Fig.10 Anchorage type B. Force-displacement diagram for cyclic loads.

RESULTS OF ANCHORAGES TYPE C

This is the most common and efficient way to anchor a steel rod (either a tendon or a reinf. bar) into the brickwall. It is easy to design the tendon, the nut and the plate, in such a way that their resistances are not critical. Fig. 11 shows that a large portion of the brick wall is involved in the collapse mode. Two yielding phases (common to all the tests of type C anchorages) are shown in the sketches of fig. 12. In the first phase (bending of the wall) the tensile resistance of brick and mortar is important, while in the second phase ("punching") the degrading shear resistance of the wall is important.



Fig. 11 Picture of anchorage type C at collapse.

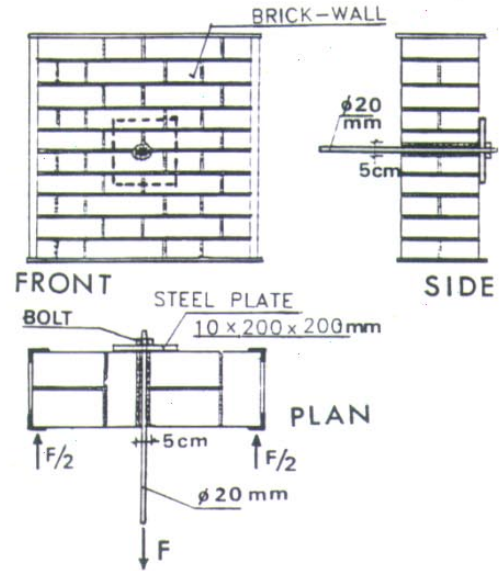


TABLE 4: Anchorages type C - Results, $P = 0$
(Units : daN)

Model -Mortar	F_{max}	F_u
C1 - M5	7900	4800
C2 - M5	8200	2600
C1 - M1	4300	4000
C2 - M1	2800	2000

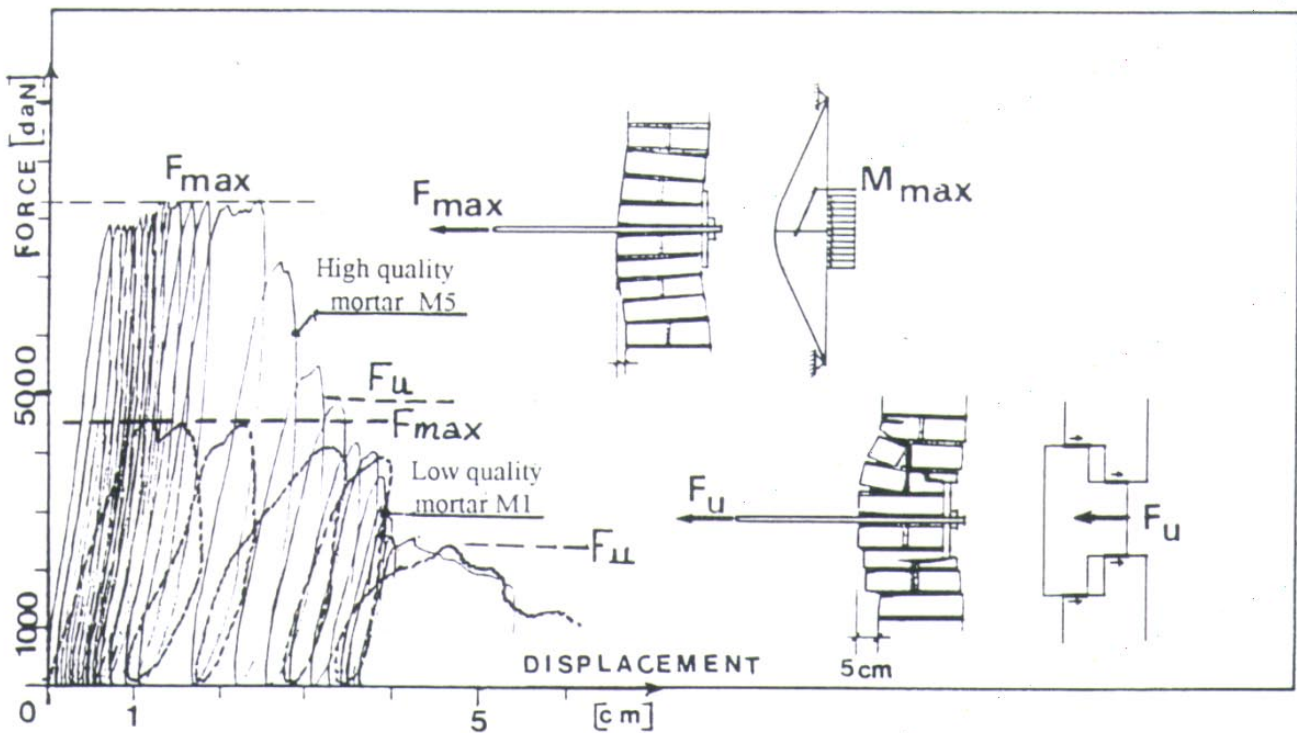


Fig. 12 Anchorage type B. Force-displacement diagram for cyclic loads

DESIGN RULES

Very few design rules appear in the literature to check the resistance of anchorages into brick walls. In ref. 3 a criterion is given, based on a sliding surface below the anchor, having a hypothetical truncated-conical shape. According to ref.3, two limit loads N_1 , N_2 , can be calculated, equilibrating either the limit friction forces (f being the friction coefficient) or the cohesion forces (i.e. limit shear stresses " c " associated to zero normal stresses " p ") acting on the hypothetical truncated-conical surface (see caption of fig. 13). If we apply this criterion to our experimental results, we find that it always overestimates the experimental resistance.

We suggest now an update criterion can be formulated, making a more general statement, namely : each anchorage type has a characteristic sliding surface, that can be determined either by experiments or by extrapolation of similar cases. If A^* is the sum of the projection of every portion of this surface in the direction of the tendon, the limit force can be written as:

$$N = A^* Q$$

Where Q is the average shear stress on A^* :

$$Q = \max (t(p) ; f \cdot p)$$

Where

- p = normal (vertical) in plane stress.
- $t(p)$ is the limit shear stress as a function of p .
- f = friction coefficient
- Clearly $t(0) = c$, average cohesion, as defined above.

The design value of N is :

$$N^* = m A^* Q$$

Where m is a safety coefficient.

Table 5 compares F_{max} , obtained from our experimental results, with N , obtained from the above simple rule. The agreement is reasonably good. Uncertainties are due very much on real "cohesion" values for masonry, especially with low quality mortar.

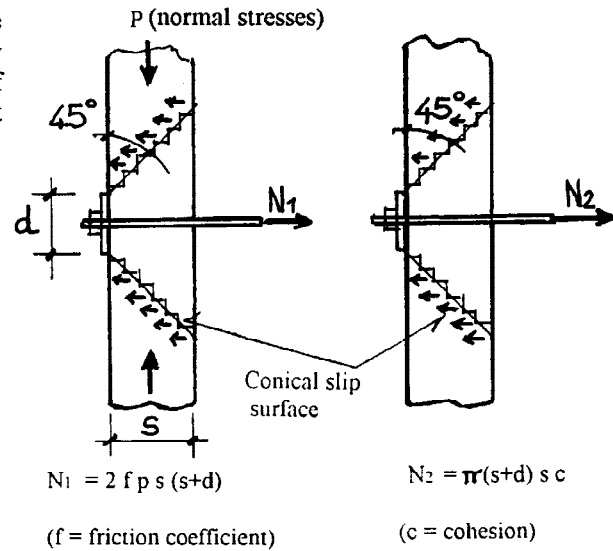


Fig. 13 - Limit states according to ref.6

TABLE 5 - Comparison between experiments and theoretical results from eq(1), (2) for $p = 0$

Type	Sliding surface	A^* into eq. (1) (cm ²)	Mortar type	Average Cohesion (experimental-tab.1) (daN/cm ²)	Theoretical force N eq. (1), (2) (daN)	F_{max} (mean of experimental results) (daN)
A	<p>lateral surface of concrete into the pocket</p>	$(2h+2b)s = 1058 \text{ cm}^2$	M5	3.37	3565	3333
			M1	1.6	1798	1692
B	<p>$h = 2$ layers (usually)</p>	$(2h+2b)s = 2254 \text{ cm}^2$	M5	3.37	7595	7500
			M1	1.6	3606	3250
C	<p>truncated pyramid</p>	$2s(d+h+s) = 2898 \text{ cm}^2$	M5	3.37	9766	9000
			M1	1.6	4636	3550

TEST WITH IN - PLANE (VERTICAL) STRESSES.

Four models were tested applying a vertical constant force P . A rubber pad was applied to distribute this force on the bricks, in order to obtain a rather uniform and constant normal in - plane stress of 5 da N/cm^2 . Low quality mortar has been used (M1). The obtained results are summarized in table 6. Comparing the results of this table with the previous (tab.5) it is clear that the presence of in-plane normal stresses increases the strength of the connection. A good agreement is obtained between experimental results and predictions from eq (1), (2), if a resistance of frictional type is sought, with friction coefficients shown in table 6.

Table 6. Comparison between experiments and theoretical results from eq. (1), (2), for $p = 5 \text{ da N/cm}^2$, mortar type M1

Type	A * into eq. (1) cm^2	F max experimental (da N)	f in eq. (2)
B	2254		
C	2898		

CONCLUSIONS

The experiments show that :

- a) the shape of the anchorage and the quality of brickwork (limit shear stresses on mortar layers, particularly) have great influence on the resistance of the anchorages.
 - c) the yielding of the anchorages subjected to cyclic (seismic) loads is not "fragile", in the sense that large displacements and many cycles must take place before the resistance decreases significantly. However, full hysteresis loops can not develop, since forces cannot invert direction.
 - d) Simple theoretical models can predict limit states, and this leads to easy design rules.
- However more experimental investigations are needed to fit proper parameters into theoretical rules.

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