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REPAIR OF EARTHQUAKE DAMAGED BUILDINGS

by

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SUMMARY

A thorough analysis of an earthquake damaged structure must be made before repairs and strengthening work can be designed and executed. First, the earthquake damage must be thoroughly investigated and the causes for the damage determined. Repairs for the damage can then be designed together with any desired strengthening to prevent a recurrence of the damage in the next earthquake. The consequences of the strengthening scheme must then be investigated in detail to insure that it does not in turn become the cause of further damaging effects. Several examples are cited.

INTRODUCTION

After all damaging earthquakes, there is a great desire by building owners to get their buildings repaired and back into operation as soon as possible. Frequently, building owners or local building or government officials will also desire or require that the building be strengthened to provide increased lateral force resistance for preparation of the next earthquake. This paper attempts to outline a procedure for this strengthening and warn of several potential pitfalls frequently observed.

DETERMINING THE DAMAGE CONDITION

The first step in repairing any earthquake damaged structure is determining exactly how the structure performed. This requires a detailed inspection of the building and a listing of all damaged elements and members. It may be necessary to open concealed areas to permit a thorough investigation and insure that hidden damage does not remain undetermined.

The engineer must then analyze the structure and thoroughly understand why the damage occurred. He must satisfy himself of the force resistant paths in the building and why certain members failed or cracked while other members were essentially undamaged. He must determine if members failed due to shear, compression, tension, flexure, bar anchorage, etc. He must consider the effects of non-structural elements such as walls and parapets. This analysis is essential before any repairs can be designed.

DESIGN OF STRENGTHENING SCHEME

Once the damage is documented and understood, the repair of individual members can be designed to return the original or desired strength to the member. Such repairs usually consist of epoxy injection, partial replacement or occasionally, complete replacement of the damaged member.

The engineer then needs to consider how to minimize such damage in the future. He may decide to strengthen selected members which failed and make them considerably stronger. He may decide to add shear walls to stiffen a frame structure. He may replace damaged non-structural walls with structural bracing walls.

Whatever strengthening techniques are chosen, the effects of the strengthened members on adjacent members and the total structural system must be investigated. If certain frame members are made stronger, will the next earthquake simply cause the adjacent unstrengthened member to fail? If a wall element is introduced, will it cause adjacent failures due to overturning forces or stress transfers? If strengthening is added in only one story of a building, will it cause increased damage in other stories of the building which were undamaged in the recent earthquake? The following section provides several examples.

SELECTED EXAMPLES

The first example involves the Colegio Teresiano on the outskirts of Managua, Nicaragua. The building is a three story concrete frame school building of a long rectangular plan, similar to schools built throughout the world. A small earthquake of magnitude 4.6 in 1968 was centered quite close to the building and caused cracking and structural distress to the columns in the first story. The building was repaired by adding a stiffened concrete wall element in the first story between classroom doors and extending up to the second floor balcony rail height. This new wall element can be seen in Figure 1.

The destructive Managua earthquake of December 23, 1972, caused considerable damage to this building, but only in the second and third floors, where considerable column damage resulted. Figure 1 was taken after this second earthquake. The new wall elements in the first floor prevented damage in that floor, but permitted the earthquake forces and motion to travel upward, causing the observed damage. The repairs had not considered the effect on the remainder of the structure. Had these or stronger walls extended to the roof, much of this damage might have been prevented.

A second example shows a three story classroom building at the Agricultural University in the La Molina area of Lima, Peru. There are four identical buildings of concrete construction. The first story was originally framed without structural walls and only columns for support and bracing. Considerable wall panels and masonry partitions were present in the upper two stories. A magnitude 7.5 earthquake on October 17, 1966, caused significant damage to the first story columns, so concrete shear panels were introduced to stiffen and brace this first story.

A second earthquake of magnitude 7.6 affected these structures on October 3, 1974. Figure 2 shows the end of one of these buildings after that earthquake. There was little damage in the first story due to the previous strengthening, but that increased stiffness caused considerable damage in the upper two floors which had not been strengthened after the 1966 earthquake.

CONCLUSIONS

The damage sustained by a structure in an earthquake must be thoroughly understood and analyzed before repairs can be designed. Repairs which involve adding strength or stiffness to a member or structure must be fully analyzed for the impact on adjacent members or stories in future earthquakes.

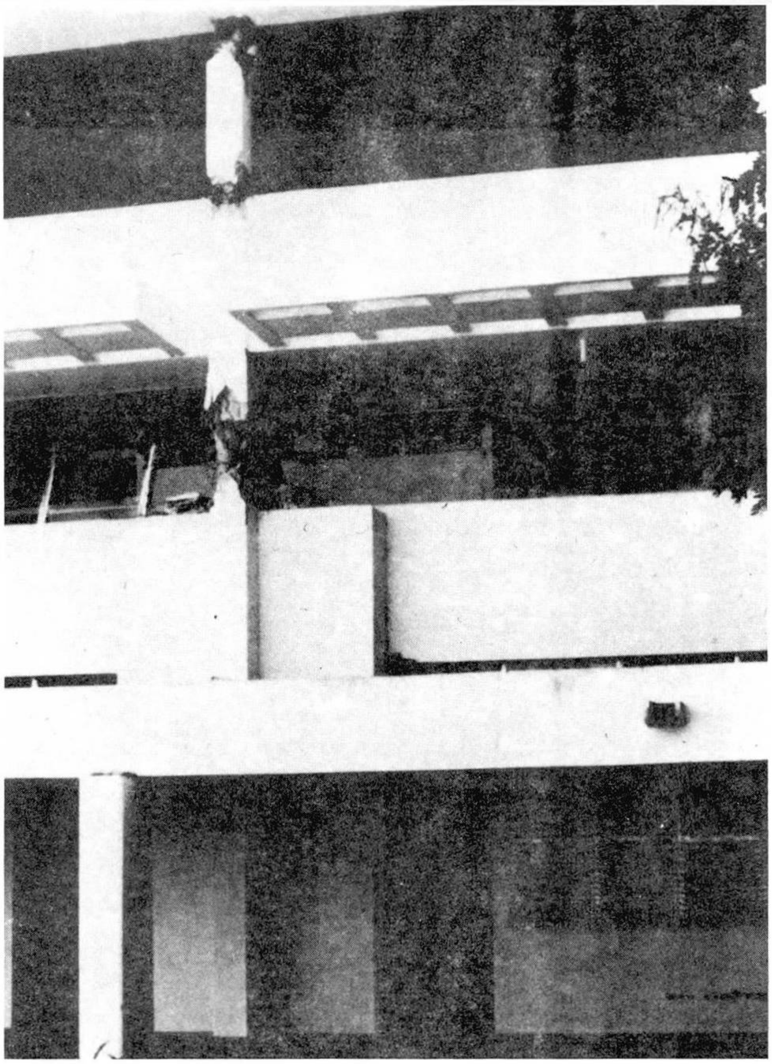

Figure 1. Colegio Teresiano in Managua, Nicaragua, after 1972 earthquake. First story stiffening wall, which can be seen projecting outward from second floor beam, prevented first story damage but increased upper story damage.

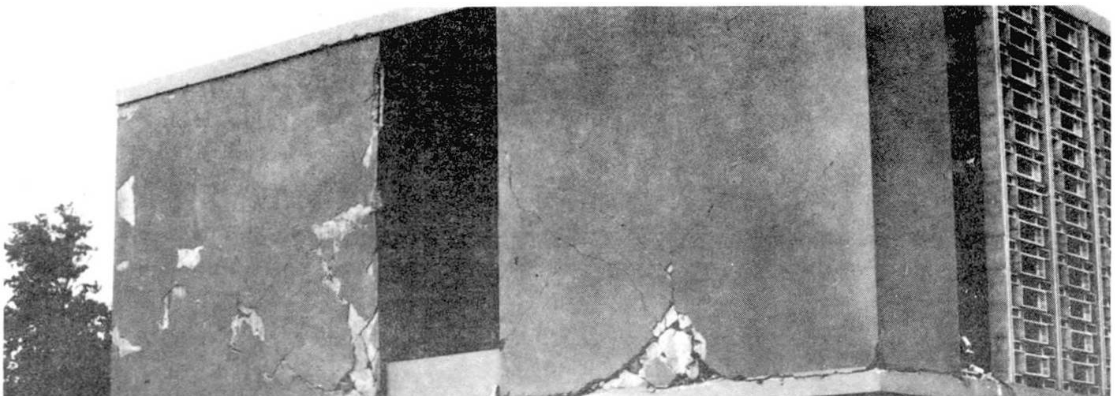

Figure 2. Classroom building at Agricultural University after 1974 earthquake. Stiffened first story had little damage due to added concrete wall panels, but upper stories had increased damage in this earthquake.

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Abstract models for the structures of a building to be restored

Les modèles abstraits des charpentes dans un projet de restauration

Die abstrakten Modelle der Tragwerke bei den Restaurierungsplan

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SUMMARY
In this paper topological models of the structures of buildings are presented: 1) as a technique for representing the mechanical models of bi-dimensional structures (plates, slabs, vaults) by graphs, as is usually done for systems of rods or beams; 2) as a guide to the invention of new constructional schemes for the reinforcement of bidimensional structures; 3) as a criterion for the choice between different mechanical models of the same complex of structures; 4) as a tool for the classification of the different kinds of statical behaviour of a complex of structures before and/or after successive earthquake damage and/or in the various stages of a restauration.

RESUME
Dans cette note on présente des modèles topologiques des structures des bâtiments: 1) comme technique pour représenter les modèles mécaniques des structures bi-dimensionelles (plaques, dalles, voûtes) avec des graphes; ce que l'on fait généralement pour les systemes de barres ou poutres; 2) comme guide pour l'invention de nouveaux systèmes de renforcement des structures; 3) comme criterium pour le choix entre modèles mécaniques différents du même ensemble de structures; 4) comme outil pour la classification des différentes possibilités de comportement statique d'un ensemble de structures avant ou après des dommages sismiques successives et/ou pendant les phases d'une restauration.

ZUSAMMENFASSUNG
In dieser Mitteilung werden die topologischen Modelle der Baustrukturen eingefürt: 1) als Technik, um die mechanischen Modelle von bidimensionalen Strukturen (Platten, Scheiben, Gewölbe) durch Graphs darzustellen, wie es gewöhnlich für Staben-oder Balkensysteme gemacht wird; 2) als Leitung für die Erfindung neuer Systeme für die Verstärkung der bidimensionalen Strukturen; 3) als Wahlmassstab zwischen verschiedenen mechanischen Modelle desselben Struktursystems; 4) als Werkzeug für die Einstufung der verschiedenen Typen von statischen Verhalten von einem Strukturkomplex vor oder nach darauffolgenden seismichen Schäden und/oder während der Restaurierungsphasen.

§ 1.- Retrieval and classification of the informations.

The first operation to be carried out in the study of each building is obviously a formal-geometrical survey: the Author suggests that this should be carried out by a photographic (not stereographic) procedure and successive restitution to the computer (CE 196, 201). The survey must include cracks or splits and must be completed by a series of technological investigations. These data and the successive deductions are co-ordinated by "levels of abstraction" in models:
M^1 at the level of the technical drawings (and of the practical geometry);
M^2 at the level of the theory of the structures (and of the affine geometry);
M^3 at the level of the topology.
The models belonging to each level are connected by the relationships between the three types of geometry. Each technical drawing in fact also contains informations of a projective type (which emerge in the models M^2) and of a topological type (which are the only ones conserved in the models M^3).
It should be noted that several M^2 correspond to a single building: as many as are the conditions of load which have occurred in the history of the building or which could in all likelihood arise.
Each of these models consists of a set of Mechanisms and Resistant Functions. We mean by "Mechanism" a sub-set of constructional elements which absorb one of the systems of loads considered without the other parts of the building being stressed and without being stressed by other forces. "Resistent Function" on the other hand is one of the forms of mechanical behaviour (if more than one should occur) by which a certain complex of constructional elements carries out its static tasks.
Another case to be considered is the collaboration of neighbouring buildings in cases of collapse or demolition (CE 71).

§ 2.- The classification of statical-constructional models is carried out by "levels" of abstraction" and by "scales". These last are generally:
scale 1 - building complex (large building, city block etc.);
scale 2 - wing of a building;
scale 3 - small set of collaborating structures;
scale 4 - constructional element or connection;
scale 5 - mural texture; bars and ties in reinforced concrete; etc.
In the higher squares of fig. 1 we see models to scale 3: one half of the set of structures which enclose a room: i.e. a partial frame composed of 4 knots, of the beams and pillars which meet in them and of the collaborating masonry panels and r.c. floors. In the lower squares of the same figure we see the models (to scale 4) of one of the said knots. The two drawings in the squares on the left are M^1 or constructional drawings; those in the centre are M^2, or static schemes; those on the right, M^3 or topological schemes.
From the example of the figure other modelisations to scale 1, 2, 3, 4, can easily be inferred. Those to scale 5 serve for the study of alterations of the mural texture as can be produced by earthquakes or by fatigue (CE 202).

§ 3.- Static-constructional analysis with models of 2 and 3 abstraction.

In the example of figure 1 the mechanical behaviour is of one kind only, at least in normal conditions: the distribution of the flexural moments in the r.c.

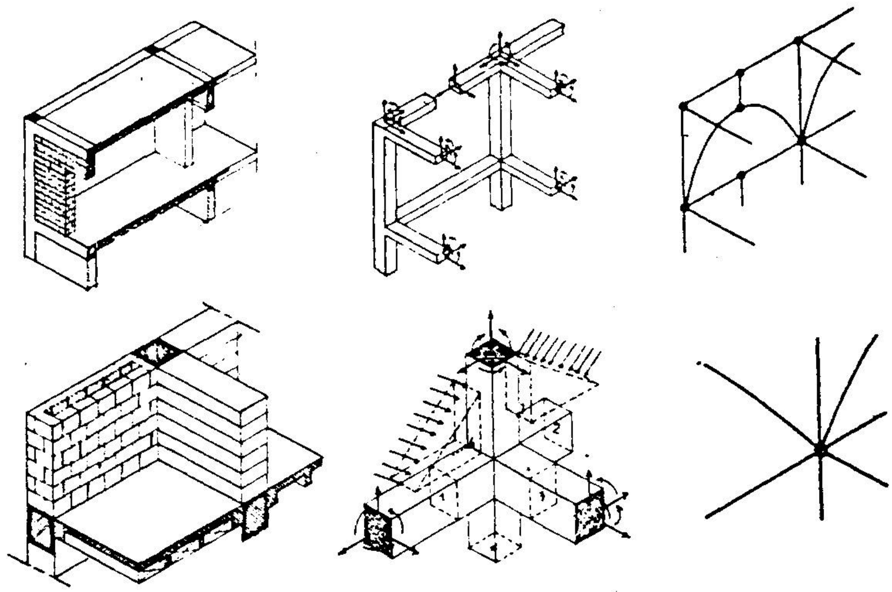


fig. 1

beams and stanchions and the isostatics in the wall panels can vary according to the loads applied but, in each case, the framework behaves as a frame and the walls as slabs.
In the case of earthquake, as is well known, everything can change, also at scale 3. With strong horizontal forces the mural panels can behave as plates especially if they are thick and heavy; and therefore flexional fractures can occur in them. If the disconnections are limited to non-essential structures, cracks or partial collapse occurs: otherwise plastic hinges are introduced in the main frame which generate resistant mechanisms completely different from the original ones; and/or cinematrical mechanisms which lead to the total collapse. With a careful study of the geometry and of the technology of the building these possibilities can be foreseen. It is therefore advisable to consider, at the 2nd abstraction, besides (or instead of) the elastic models, limit state models both in the global study of the building, scale 1, and of its parts on the successive "scales".
For other and more complex constructions, still at 2nd abstraction, the static interpretation cannot be given satisfactorily by using a single elastic model. Let us consider, for example, a centrally symmetrical (domical or fan or rib vault) fig. 2;it will work generally according to three distinct static functions: (i) membrane, if stresses S, H are balancing the external loads by effect of the curvature; (ii) plate if only the stresses Q_s, Q_h, M_s, M_h, $M_s^{\cdot}$, $M_h^{\cdot}$ are acting; (iii) slab if the stresses S, H, T balance themselves in the plane tangent to the vault.

For every voussoir quoin (on the basis of the relative size of the above mentioned sets of stresses) and globally (in proportion to the work of deformation produced in the whole dome by each system of stresses) it will be possible to determine how much of the load is entrusted to each resistant function and to represent this tri-partition by a point of a typologies triangular diagram (fig.3).

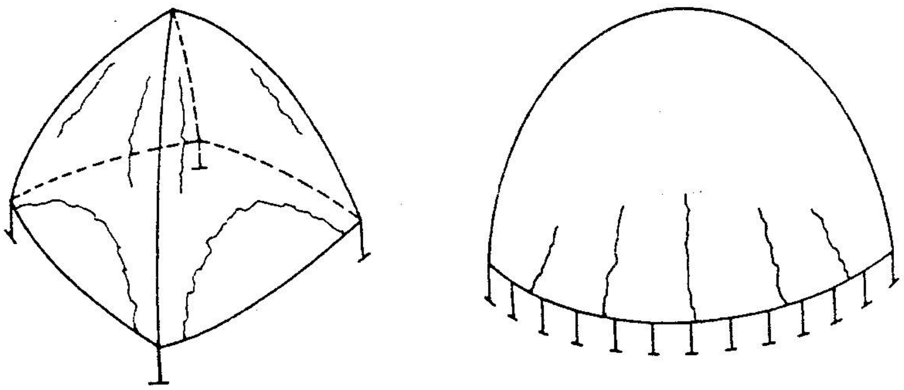


fig. 2

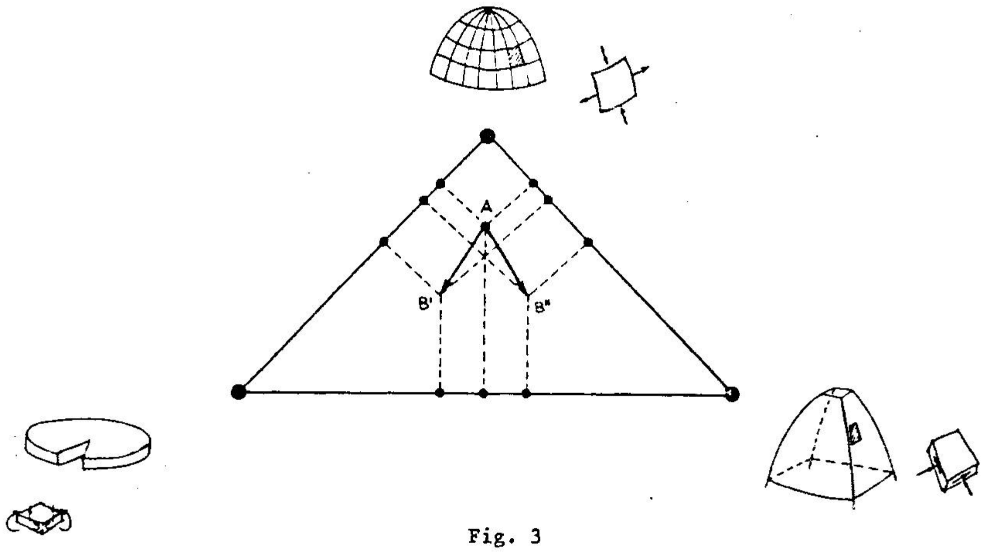


Fig. 3

For any modification of the physical state of the vault (e.g. cracks or partial collapses) there will be a variation of the tri-partition: the representative point will pass in B" (increase of the plate effect produced by settling of the bearing structures or by arched cracks on the base of the vault); or in B' (increase of the slab effect revealed first by cracks in accordance with the meridians).

The plate effect produces τ stresses which in cloister domes (cupole a padiglione) with continuous support can cause oblique cracks (or also cracks according to the meridians because ring stresses are contrasted by the friction) in the upper part of the haunches, as in S.Maria del Fiore. With discontinuous support we have also arched cracks in the base of the vault.
The slab effect, added to the membrane traction, produces cracks according to the meridians at the base of the dome, as in St. Peter's.
Two interesting examples, one seismic, (a partial collapse in the dome of the Gesù Nuovo, 1638, CE 118) and the other from war damage (partial collapse in the dome of the Gerolomini, 1943) have occurred in Naples; a similar phenomenon, revealed by arched cracks has been observed by ing. Jannaccone in the dome of the church of Monte Calvario in Foggia.
Improvident measures of "destructive" restauration such as the dismantling of the dome of the Gesù Nuovo in Naples in 1760 or, to quote a far more modest but

recent episode, the demolition of the barrel vault (S.Leonardo hospital at Castellammare di Stabia, CE 71) have caused considerable damage to the supporting structures through alteration of the counter-thrusts in the buttresses; experiences which are useful also for interpreting the chain-collapses originating from a first occurrence (partial collapse) and further partial demolitions.

§ 4.- Panelled frames.

In the study of the masonry enfilled r.c. or steel frames the model of 3rd abstraction, i.e. the graph of the connections (drawings on the right of fig. 1) is well known: this model was proposed by Fenves (1963) for programming the computer calculation of steel frames and by the Author (CE 120) for checking the identity of statical behaviour between frameworks the schemes of which are mutually reduceable by operations on the graphs.
It is observed at this point that it is easy to study with the same method the alterations in the scheme of the connections owing to partial collapses and or to erroneous partial demolitions of a r.c. frame and also, as will be seen below, of more complex structures.
After having obtained at topological level (3rd abstraction) a rough idea of the distribution of the stresses in the whole building before and after the partial collapses, we have a trace which must be followed in the study of the model of 2nd abstraction, i.e. in the usual structural analysis.
A first interpretation of the phenomenon at the 3rd abstraction is useful also for flat frames with strutting panels in order to be able to set out correctly at 2nd abstraction (static scheme) the study of mechanical behaviour under horizontal stress.
According to the global slenderness of the ribbed wall (which in multi-floor buildings with standard ratios between the span of the bays and the height of each floor is a topological feature we have, fig. 4, two distinct types of behaviour under horizontal stresses corresponding respectively to the two elementary models for quick calculation: inflected cantilever (left-hand figure), and frame subjected to simple shear (figure on the right).
The picture of the isostatics corresponds respectively to that of a unique plate (representing the whole frame) and to those of the single panels enfilling each bay of the frame: a double possibility confirmed by photoelastic experiments in

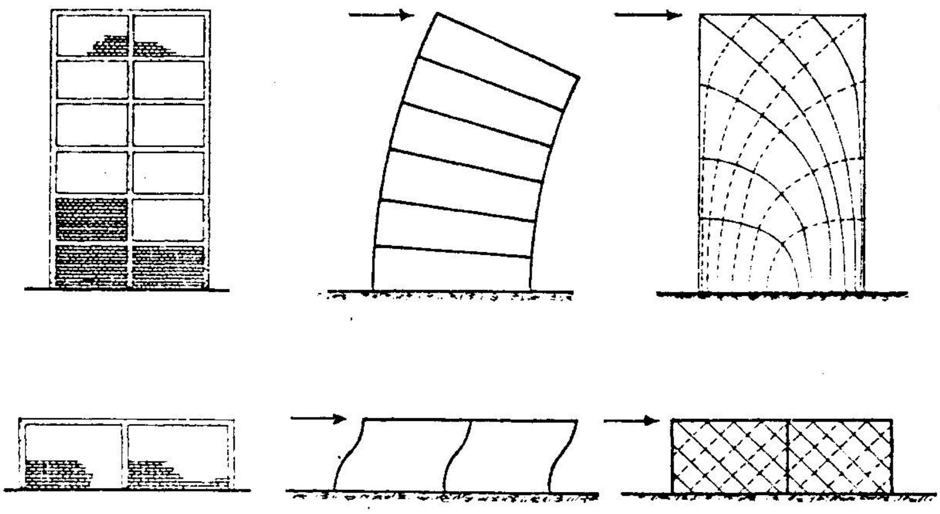


Fig. 4

course (Rienzo).
The standard method by which each panel is individually substituted in the calculation by a diagonal connecting rod is thus not generally to be applied.

§ 5.- Topological model of a simply supported plate.

In order to use in those constructional systems the graph of a framework as an M^3, it is necessary to define the line or the sub-graph (set of lines) corresponding to each of the bi-dimensional structures in question.
At scale 5 the M^2 for a plate supported at the ends can be a set of crosses of bars hinged in the points of contact, as Wyss has widely illustrated; at the 3-4 scale (fig. 5a,b), a discharging arch can be substituted for the plate and thus a single line in the graph; line which represents at the 3rd level of abstraction the complex of the compression isostatics. We need four lines in the graph if the traction isostatics are taken into account: i.e. one line after and four before the opening of the craks which physically give origin to the discharging arch.
To conclude, we must compare the topological scheme derived in fig. 5b from the isostatics of fig. 5a (a plate supported at the ends), with the isostatics of fig. 4 (a plate acting as a corbel which represents a panelled frame stressed by horizontal forces); it will be easy to derive by comparison the corresponding topological scheme (M^3) for this frame.
Note also that seismic stresses can also produce an alteration of the texture of the material. It is clear that in such a case the phenomenon of the discharging arch survives approximately and hence the possibility of representing the wall with a single line of the graph until the static function of the panel is completely annulled.

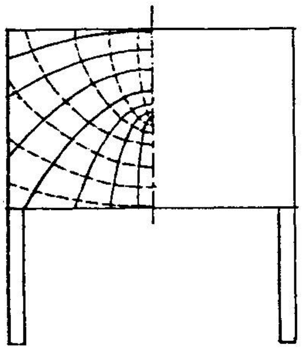


Fig. 5a

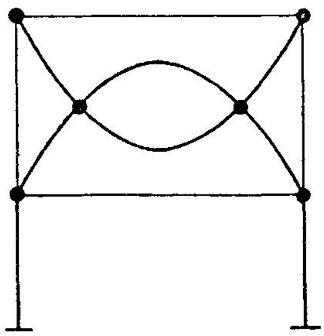


Fig. 5b

§ 6.- Topological model of the slab.

We try here to identify the M^3 of an elastic slab, a bi-dimensional structure stressed perpendicularly to its plane, meaning by M^3 the topological scheme of a set of rods (M^2) having the essential connections of the bi-dimensional structure assigned.
We accept the same limit set up for the plates in the preceding § 5, i.e. the M^3 for which we are looking should be valid for a single and specific condition of

load which however in this case is the most usual and practically the only one compatible with the definition: loads all normal at the plane of the slab. The technique is identical: to find a set of few rods which can take the place of the characteristic lines of the continuous mechanical scheme.
The difference is that whilst for the plate stressed by external forces acting in the middle plane we have taken into consideration the orthogonal network of isostatics (replacing it by several rods subjected to axial strain), for the slab we propose to substitute for the orthogonal network of the lines of max/min bending moments a small number of inflected beams.
Fig. 6a shows the well known picture of the lines of max-min moment for a square slab subjected to perpendicular load uniformly distributed supported by four beams at the edges: fig. 6b shows a scheme of inflected beams (B_1-B_2, B_2-B_3, B_3-B_4, B_4-B_1; B_1c, B_2c, B_3c, B_4c) which we will suppose equivalent to the slab: to which we add the beams of support and the pillars placed at the vertices.
Considering fig. 6b as a sub-graph, we shall have indicated a way of inserting sub-model M^3 of an inflected slab into the graph of the connections of a complex structure, made up of slabs and beams.
It is interesting to observe that from this M^3 can be deduced an M^2 (mechanical scheme) of the slab under examination, no longer in elastic regime but at limit state. We have in fact traced in fig.6c the dual hypergraph of the graph which representes the slab (cp. CE 188) or, if preferred, the dual graph point-line according to Nakajima.
In this every line of the original graph is replaced by a dot (which represents the section in which the beam represented by the said line in the original graph bears the limit value of the moment) and every node is replaced by a line. These lines (fig. 6d) represent the lines of fracture which are typical of the slab supported at the edges.

Fig. 6a

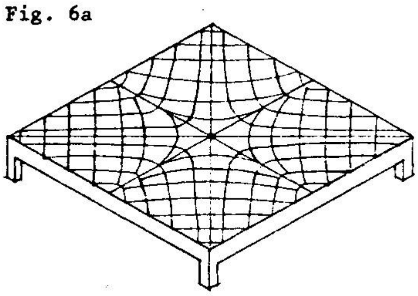
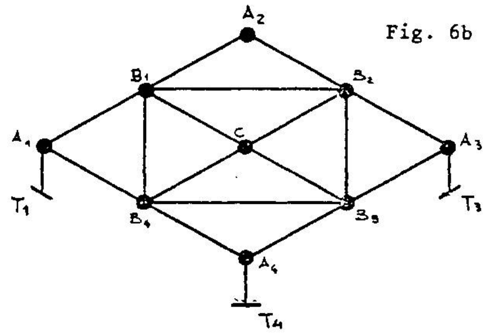


Fig. 6b



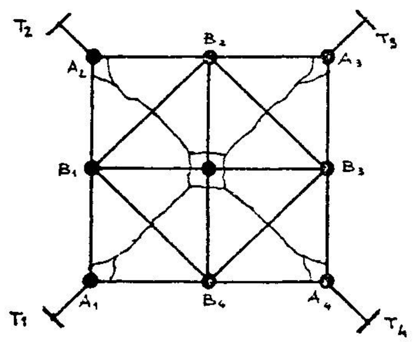


Fig. 6c

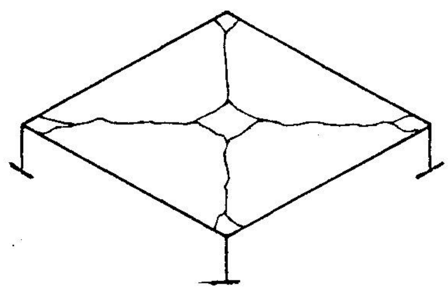


Fig. 6d

The second example refers to a mushroom floor. For this the isostatics are given in fig. 7a and the graph in fig. 7b. Fig. 7c shows the dual graph for a

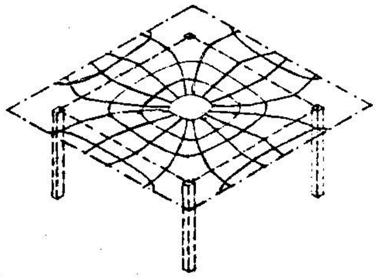


fig. 7a

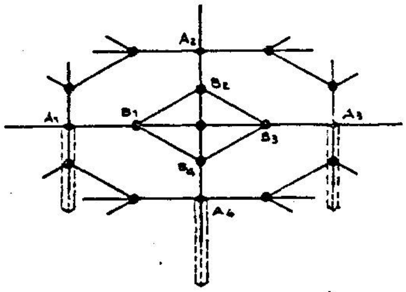


fig. 7b

generical field of the continuous slab and part of the adjacent fields. Then in fig. 7d the lines of fracture of a single field with some adjacent elements have been constructed.
It is also interesting to observe the repetitive symmetry of the dual graphs of fig. 7c which represent, superimposed, the abstract models (monodimensionalised) respectively of the elastic model and of the limit model of the mushroom floor.

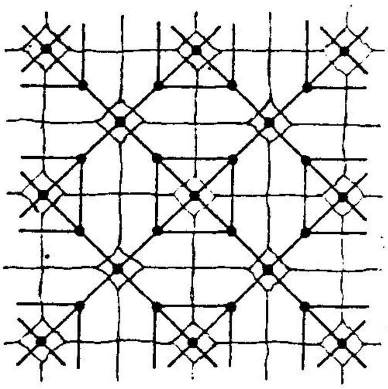


fig. 7c

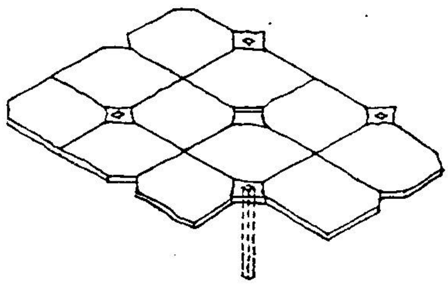


fig. 7d

§ 7.- Observations on the modelisation.

Lately we have compared the graphs representing the repetitive structures and the tessellations of the plane or of the space. Analogous observations have been made for some time for elastic frames and serve to explain, for these last and for continuous beams, the continuing form of the matrices of the systems of linear equations which represent them (CE 62).
From what has been said clear indications can be inferred analogously on the systems of equations relative to continuous slabs.
We now recall that in § 5 and 6 we limited ourselves to defining, both for the slabs and the plates, some M^3 which correspond to only one of the possible conditions of load and that, in the M^2 made up of rods or of beams (figs. 5b and 6b, 7b respectively), we built resistant mechanisms in which we show up only the connections acting in the specific conditions of restraints and loads.
In order to represent a generic and complete picture of the connections in a slab or plate with a mechanical scheme (M^2) or a topological one (M^3), without emphasizing any particular conditions of loads, it is necessary to bear in mind the tensorial nature of the mechanical models of the bi-dimensional structures.

This, together with the hypothesis of geometrical and mechanical linearity, allows us to substitute for the continuous bi-dimensional M^2 a triangular tessellation of the plane or of the surface under consideration (fig. 8).

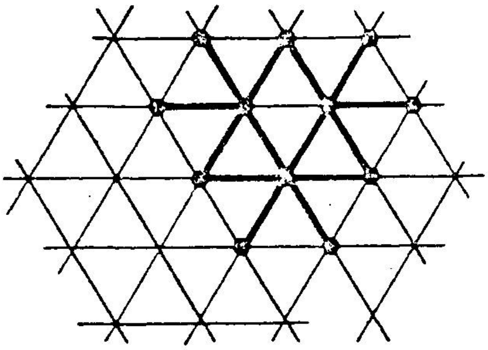


Fig. 8

In other words the more general graph of a bi-dimensional structure, restrained and stressed in any possible way, is made up of a set of lines disposed according to this tessellation and along each of which is transmitted a bending moment or an axial strain according to whether we are dealing with an M^3 relating to a slab or a plate.
There remain to be studied the relationships existing between the model of fig. 8 and the specific ones illustrated in figs. 5,6,7 for particular conditions of load and for this the concept of "scale" introduced in § 2 is valid.
If the supporting surface of the bi-dimensional continuous models is not flat but curved the considerations made in § 4 of part I of this study (CE 220) are brought into use.

§ 8.- Conclusion.

The few examples inserted in these pages are intended to introduce a simple procedure for the structural analysis of existing buildings, a procedure which will be used in a future work on static restauration design: the methodology described is in fact based, as in CE 215, on the comparative and global study of the static and topological-static models of buildings.

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