DEVELOPMENT OF DEMOLITION TECHNOLOGIES: ANALYSIS OF THE COLLAPSE OF A BUILDING PULLED DOWN BY EXPLOSIVES

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Summary

The demolition and rubble recycling industry is emerging as an alternative sector of the extractive industry and its development is fundamental from the environmental point of view. Concepts developed by the extractive industry find close analogies in demolition-recycling activity. The material processing relies on similar physical principles, and the same similarity is broadly observed in plant layout. The studied case is the side toppling of a 36 m high building, whose bearing structure was made of reinforced concrete factory cast walls and ceilings. Upon removal by mechanical cutting of a part of the walls, the remaining part of the bearing structure was blasted. The fall was studied through motion picture analysis, vibrometric records and numerical analysis, with the main aim of obtaining information on the resisting forces acting during the collapse. The practical objective was to obtain information and rules for the design of the basal notch and of the preliminary weakening, in similar cases, allowing a control of the fall direction and of the distance reached by the falling object. In the concluding remarks, the advantages of combined mechanical cutting/drilling and blasting methods in building demolition and the importance of a reliable forecast of the collapse dynamics, are properly underlined.

1. Introduction

Beside the traditional extractive activity and beside the construction industry, the demolition sector and construction and demolition waste processing and recycling field are becoming more and more remarkable as emerging and alternative activities, from both the technical and the environmental point of view. The concepts developed by the extractive industry find close analogies in demolition-recycling activity: bulk vs selective exploitation finds a parallel in the explosive vs mechanical demolition; unwanted effects control is a common problem dealt with in a quite similar way.

Concerning the project planning, the demolition technologies have to be improved in order to optimize the building collapse. Moreover, a new building has a use-phase duration variable, on average, from 50 to 100 years. After this period, it is necessary to optimize the end of life phase through the development of innovative demolition technologies; for this reason, in few Countries, as USA or UK, together with the construction design, it is necessary to drawn up the demolition plan.

Finally, the recycling of the construction and demolition waste in adequate processing plant allows to produce secondary raw materials with physical-mechanical characteristics similar to the ones of the natural aggregate, aimed to the optimization of the primary resources exploitation and to the development of the by-products market, following the life cycle philosophy and going beyond the obvious pollution avoiding concepts.

2. Demolition and rubble recycling

Besides demolition and rubble recycling activity, unavoidable consequences of the urban rebuilding programs and of the lack, in the surrounding of the towns, of ample spaces for dumping sites and for aggregate quarries, a recycling activity is becoming important, consisting in applying mining and mineral processing concepts, techniques, machinery and plants to the new sector. Indeed, a building due to be demolished can be considered the analogue of an unexploited ore-body. Seen from the mining point of view, in the demolition-recycling of a building successive stages can be recognized, functionally equivalent to “prospection”, “development”, “exploitation” and “ore processing”.

Buildings due to be demolished are much younger than ore-bodies, but not better known: in the 50 – 100 years time lapse between construction and demolition building materials and methods change, variants and repairs more or less accurately recorded are made, technical documents and drawings are lost or spoiled, moreover the strength properties of concrete, bricks, reinforcing steel are affected by weathering and aging. To comply with the obvious requirement of assured stability during the demolition work, to exclude premature collapse, coring and inspection by geophysical methods can be necessary.

Another point to be investigated in the preliminary study of the object to be demolished is the behaviour of the materials under the attack of the cutting and breaking machines (hammer breakers, saws, cutting drums and so on), born in the mining sector or adapted from mining machines. Performances of these machines quoted in the technical literature usually refer to natural materials. It is useful to indicate the "equivalent rock" of man made materials in an excavability scale.

As in mining, to make possible the "exploitation" the body is subjected to preparatory works aimed to divide it in parts, to create free surfaces and free volumes, to provide access to the working places. In this preparatory work, irrespective of the demolition method (progressive demolition from top, roughly equivalent to top slicing in mining, or induced collapse, roughly equivalent to block caving), are often needed two kinds of operations: sectioning, which means to interrupt the mechanical continuity of the building by creating the equivalent of an expansion joint, and windows opening, which means to partly remove bearing walls. The preparatory work used to be done by painstakingly removing the concrete with hammerpicks and cutting the bars by torching, but presently is greatly eased by the use of diamond saws (wire and disk saws), formerly used in dimension stone extraction. Steel bars do not represent a serious problem, accounting for a very small fraction of the cut section.

The equivalent of exploitation is the demolition proper. Different from mining, where test explosions can provide some information to design a blast with limited seismic effects, blasting and collapse vibrations forecasting from a demolition can be based only on the analysis of literature data, and collapse vibrations can be kept under control mainly by appropriate shock absorbing measures or fractioning the impact, which is not always practicable.

The rubble is a "complex ore", whose most prized component is the metallic scrap, while the most noxious impurities are the lightweight materials (wood, plastic, cardboard, plaster), and whose composition and structure is extremely variable. The bulk of rubble mass, appropriately crushed, sized and cleaned, can be used as aggregate, though of somewhat lower quality than a natural aggregate. The simplest process implies crushing, removal of reinforcing bars by magnetic separator and sieving, and is within the reach of small mobile plants. The product is mostly employed by the roadmaking industry. Acceptance controls essentially bear on grain size distribution. More sophisticated processes implying a separation stage, are possible in fixed plants, whose viability is warranted for yearly production rates around 200.000 t.

3. Analysis of the collapse of a building pulled down by explosives

3.1 Introduction

In demolition blasting, the assured complete collapse is the main objective, being very costly and dangerous to re-work a partly demolished building. When the side toppling method is adopted, it is commonly believed that the respect of a simple geometrical condition, proposed by Oehm (1992) (Figure 1), warrants complete collapse; it is surmised, however, the fact that the formula refers to an ideal, rigid, massive structure, as the quoted paper warns.

The study of an actual collapse, here presented, provides a somewhat more complex picture of the phenomenon. Let us first briefly describe the building, the preparation work and the blasting plan.

3.2 The building and surrounding structures

The 40 years old building located in Via F.lli Garrone 73, Torino, Italy, was intrinsically hard to blast down. Indeed, it was not a conventional tall building with a bearing skeleton made of reinforced concrete pillars and beams, rather a structure made of superposed layers of cells, composed of factory cast reinforced concrete walls (15 cm thick) and slabs (20 cm thick) assembled according to the prefabrication method TRACOBA, quite popular in the '960s. The concrete was of excellent quality: cores taken before the blast have shown a compressive strength of 40 to 50 MPa; the reinforcement consisted of one or two electro-welded steel meshes (diameter of wire 4 mm) and steel bars 10 to 12 mm diameter. Four elevator towers, also made of factory cast reinforced concrete elements, further increased the stiffness of the building.

Geometrical and mass features were: gross volume: 22000 m^3; mass: approx. 8000 t; number of floors: 10; total height: 36 m; length: 57 m; width: 11.5 m. One expansion joint at mid length. The original drawings and static calculations were not available. Other buildings, at 30-40 m distance, did not cause concern, but an important road, with underlying piping, was dangerously close. A wide enough free area was available to accept the rubble, on the toppling side, apart from a limited overlap, to be avoided, on the said road.

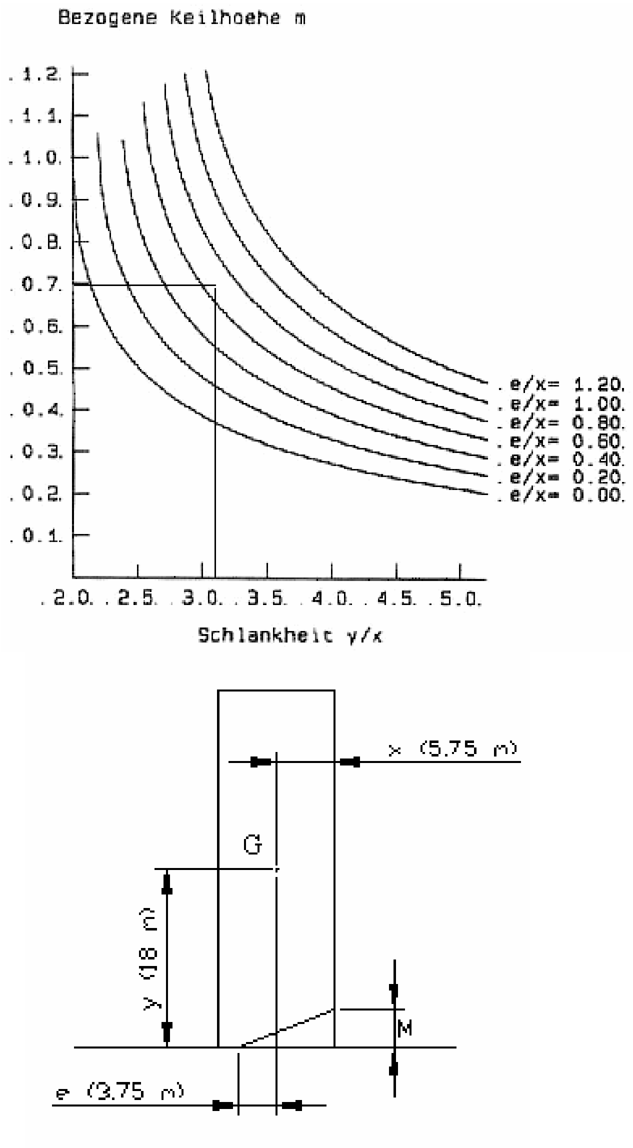


Figure 1. Up: nomogram (Oehm, 1992) to determine the minimum height of the notch; down: explanations, with reference to a tower like object; bracketed numbers refer to our case. M: height of the notch; G: centre of mass; y: height of centre of mass; x: distance of the centre of mass to the front wall; e: eccentricity; y/x: slenderness ratio. To establish the height of the notch M, using the nomogram: calculate the slenderness ratio (in our case, 3.13), select the appropriate e/x curve (in our case, 0.75) and read, on the vertical axis, the ratio m (in our case, approximately 0.7) which has to be multiplied by x (in our case, 5.75 m) to obtain M (in our case, 4 m, which practically means 2 floors, being the height of a single floor around 3 m).

3.3 The preparation works

In the fall area, three parallel trenches 2 m deep were excavated, and three earth mounds were erected with the excavated material, to damp the impact of the falling building and the ensuing earth vibration. The measure proved to be very successful, since the vibration levels due to the collapse were lower by approximately 50% with respect to the values predicted by current formulas. A big problem was posed by the real structure of the building, resting on thin but strong bearing walls instead of pillars. To efficiently crush a thin wall requires an enormous number of small, closely spaced charges; in the case, it was calculated that, to open a reasonable notch at the basis of the building, more than 20000 charges had to be used.

It was decided, therefore, upon a calculation of the percentage of the load bearing area that could be safely removed (that means, still assuring a safety factor approximately 3) to open windows in the bearing walls of the two lower floors; so doing, the building bearing structure was changed, from one based on bearing walls to one based on pillars with a rectangular or cross-shaped section, much easier to blast. Even so, the number of charges needed was very large, approaching 5400, but was considered acceptable: indeed, it was possible to charge in one shift.

The preliminary weakening work, to prepare buildings for explosive demolition, is usually made by pneumatic pick, and by cutting the bars with a torch. We proposed, in this case, to cut the reinforced concrete by diamond disc saw, which proved to be quicker and less disturbing.

The facades, having not bearing function, have been completely removed from the two lowest floors on the fall side, mainly to provide easier access and more light to the operators; the removed facade panels were replaced by a double layer of strong wiremesh to stop flyrock, a measure which proved to be effective.

The problem remained of respecting the road. To this aim, a vertical joint was created by cutting the building by means of a diamond wire saw (a single loop of wire was used), dividing the building in two parts, so that the largest part could be blasted first, finding enough free space to avoid the invasion of the road, and the smaller, immediately after the collapse of the first, could be blasted with a fall direction at right angle with respect to the first, towards the freshly formed rubble heap. The sequence is explained in Figure 2.

The cut was completed in a surprisingly short time (6 hours of machine work) and went out perfectly straight; no displacements were observed, anyhow some timber props were installed, to exclude any danger of instability of the working floors (1st, 2nd and, partly, 3rd stage). Apart from the bearing wall sections, mechanically removed, no rebar was cut.

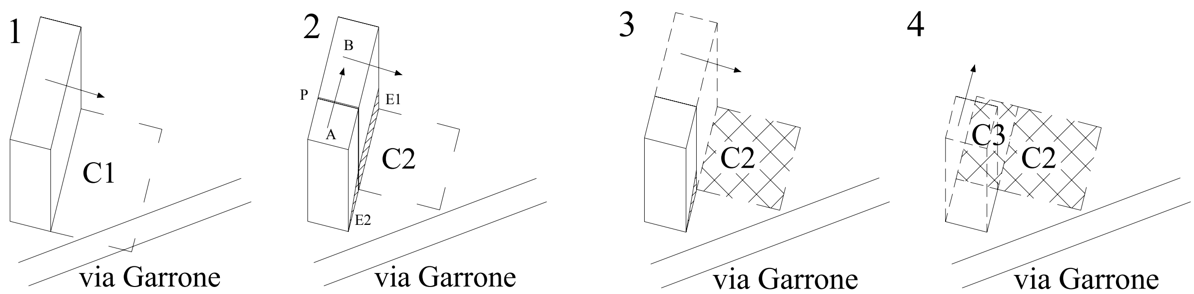


Figure 2. 1: The toppling of the whole building was due to intercept a road (Via Garrone), with the fall area; 2: A vertical joint, created by means of a diamond wire saw, divided the building in two parts; 3: the largest part of the building had to be blasted first; 4: the smaller part had to be blasted after the collapse of the first, with a fall direction at right angle with respect to the first.

3.4 The drilling and charging

Elevator and stair towers were drilled and charged up to the 3rd floor, the remaining part up to the 2nd floor on the front wall (fall direction) side, and 2 meters were spared, adjacent to the opposite wall, to provide a firm enough hinge to the rotating body. Cellars were spared too, to exclude a vertical, or near vertical, collapse. The vertical collapse option had been discarded in the preliminary discussion, because required a blasting work at higher stages than 3rd, with flyrock problems, to obtain a complete destruction, implied more drilling and mechanical cutting work, and did not warrant the respect of the available fall area.

Drilling was made with hand held drills; most of the holes were no more than 10 cm long, due to the small thickness of the bearing walls and to the impossibility of drilling holes parallel to the wall surface. Longer holes were possible only in some special point, for example in the walls of the elevator towers.

A total of around 5400 holes has been drilled. Diameters were 25 to 30 mm. Charges were typically 35 g of G.D., obtained by cutting conventional cartridges. Stemming was, obviously, symbolic (a few centimeters of sealing foam), with the main function of keeping in place the charge and the cord.

Each structural element, which means the spared parts of the former bearing walls, was prepared with 15 to 30 charged holes, arranged in bands, and connected with detonating cord. Detonating cord ends were then grouped and connected to HU short delay detonators: 9 delay times were used. Care was taken to establish cord paths minimizing the danger of cutoff and to protect the critical stretches of the cord path.

As to the section of the building to be blasted after the collapse of the first part, say some 10 s later, the blasting was prepared in the same way, apart from the fall direction but, being not available compatible detonators with so a long delay time, it was decided to use a separate blasting line, to be powered after the fall of the first section. This caused some trouble: despite the care taken in selecting a safe path for the line and to protect the ignition system, the circuit was damaged by the first explosion. For a while (30 minutes were needed to find out the defect and to reestablish the connections) the quarter of building stood un-damaged, close to the rubble heap, showing, at the upper floors, the sections of some sanitary neatly cut by the diamond wire, still hanging to the walls. That means that no friction occurred, and no forces were exchanged between the collapsing and the still standing part. Apart some difficulty in refraining the curious, the blast, however, was completed according to the plan, and the effects matched the predictions: no rubble (not even fly-rock) outside the design perimeter, vibration levels within the anticipated limits, some predicted window breakage. Total consumption of explosive was 220 kg; the height of the rubble heap was 8 to 10 m; the noise was quite strong, due to the large use of detonating cord.

4. The analysis of the collapse

The following part refers only to the collapse of the main section of the building. Indeed the event, being the first large demolition work by explosive in Turin, was recorded in detail by the local television, from a number of points, and the records have been kindly made available for our study; but this applies only to the main event, the collapse of the main part of the building. Due also to the unpredicted delay, the second event was not so completely recorded.

Information on the timing of the stages of the collapse was obtained also from the vibrometric records, especially for the late stages.

It has to be recalled that, due to the presence of an expansion joint, actually two independent bodies toppled separately, though almost simultaneously: the part between the diamond wire cut and the expansion joint, and the part behind the expansion joint (Figure 3).

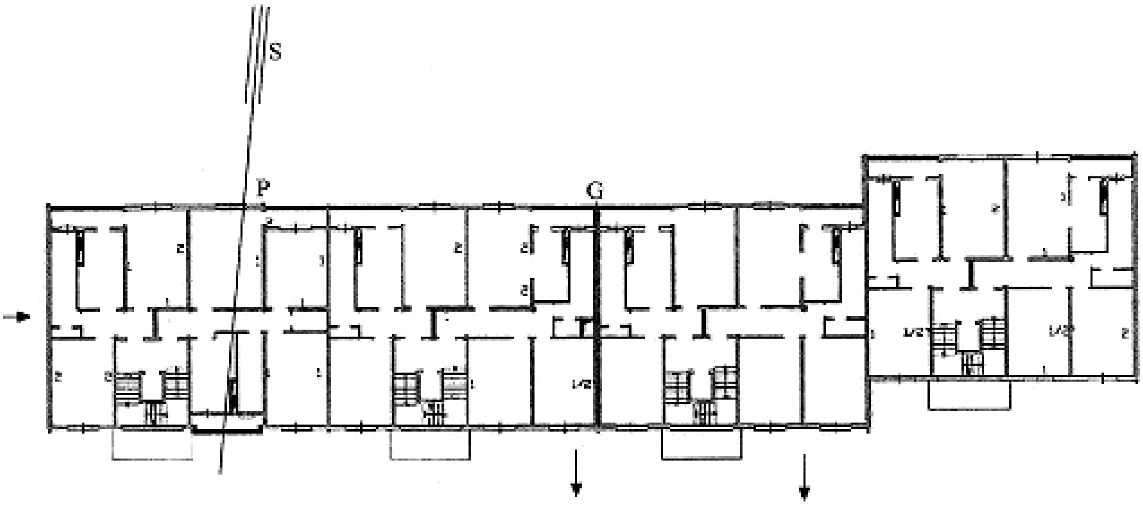


Figure 3. Horizontal section of the building, showing the position of the vertical cut P made by the diamond wire (the rails of the sawing machine are indicated by S), the expansion joint G, the fall directions of the parts (arrows).

The study of the motion of the falling building has been based on 25 frames/s TV pictures taken from a point close to the long axis of the building, parallel to the ideal hinge of the rotation, having as fixed reference the still standing part of the building, to be blasted in a later stage. The upper part of the building behaved as a rigid body, with no apparent deformation or breakage up to the impact.

To effect the calculation of the forces exchanged between the falling object and the ground, the mass, the position of the centre of gravity and the barycentric moment of inertia of the falling part of the building (not of the standing building) have been determined, referring to a vertical slice of it, of unit thickness (the problem is assumed to be bidimensional). The scheme, in an arbitrary instant of the collapse, is shown in Figure 4; to be noticed, the intersection of the axis of the reaction force with the ground changes during the collapse.

The dynamic equilibrium equations, referring to horizontal and vertical displacements and to rotation, are:

$$H - m\ddot{x} = 0 \qquad (1)$$

$$V - m\ddot{y} - mg = 0 \qquad (2)$$

$$Vbsen(\vartheta + \beta) - Hb\cos(\vartheta + \beta) - I\ddot{\vartheta} - M = 0 \qquad (3)$$

where:

m: mass

$\ddot{x}$, $\ddot{y}$: acceleration along x and y axis

b: distance between the axis of forces application and the barycentre of the mass

g: gravity acceleration

ϑ : inclination angle of the building referred to the vertical

$\ddot{\vartheta}$: angular acceleration of the building

β: inclination angle of the b segment referred to the direction of the lateral walls.

From these equation, we obtain:

$$H = m\ddot{x} \tag{4}$$

$$V = mg + m\ddot{y} \tag{5}$$

$$M = Vbsen(\vartheta + \beta) - Hb\cos(\vartheta + \beta) - I\ddot{\vartheta} \tag{6}$$

Vertical, horizontal and angular displacements, as a function of the elapsed time, have been obtained from the cinematic description of the motion, thanks to the cinematic record (TV frames, corrected for perspective and scaled).

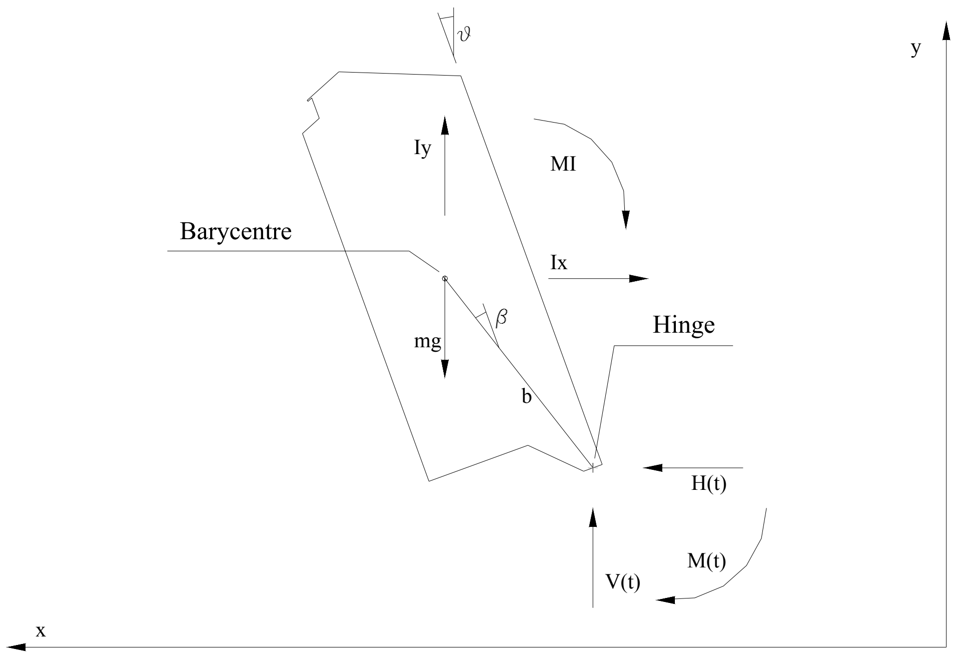


Figure 4. Scheme of the dynamic model of the structure, in an arbitrary instant of the collapse. Forces and momentums agents on the structure are indicated.

5.1 Cinematics

Three stages can be distinguished, starting from the blast: I) the build up of a hinge; II) the first contact and the crushing of the lip of the notch, which could also be termed: the migration of the hinge; III) the final rotation, up to the final impact. The temporal succession of the stages can be related also to the vibrometric record, with a good agreement to the analysis of the frames, which proved specially useful in the reconstruction of stages II and III. Figure 5 shows the position of the gravity centre, as a function of the elapsed time, at intervals of 4/25 s (four frames): stage I is mainly a downward motion associated to a rotation; in stage II, starting approximately 40/25 s after the blast, the path of the centre of gravity gradually changes, reaching stage III, where the path is circular. Figure 6 shows the positions of the falling building in stages I-II at selected instants, as reconstructed from the frames; obviously, the crushing of the lips of the notch has not been directly observed: is inferred from the geometry of the observable part and from the seismic disturbance record.

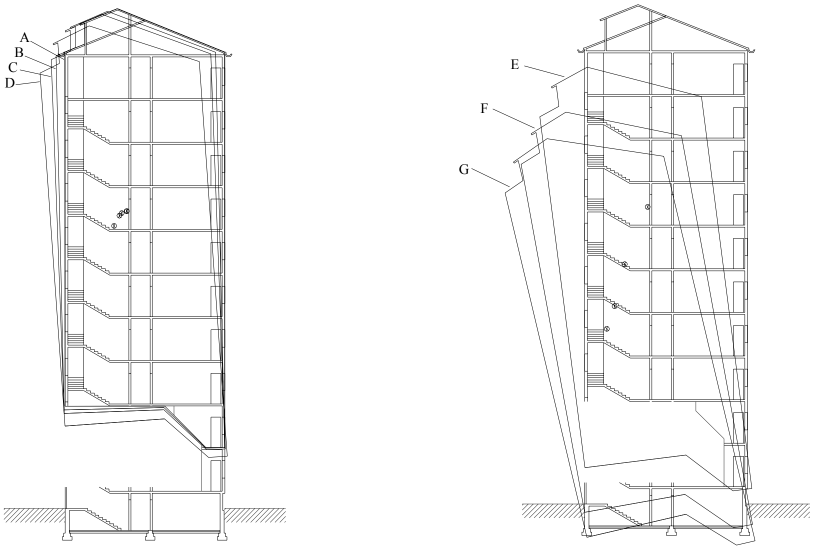


Figure 5. Positions of the centre of gravity, as a function of the elapsed time, at intervals of 4/25 s.

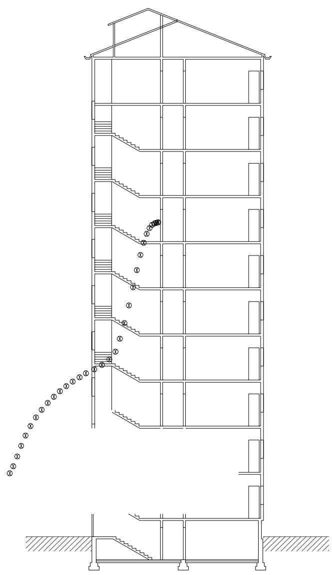


Figure 6. Positions of the falling building in stages I-II at selected instants, as reconstructed from the frames. A: 0.2 s; B: 0.69 s; C: 0.84 s; D: 1.16 s; E: 1.64 s; F: 2.04 s; G: 2.23 s.

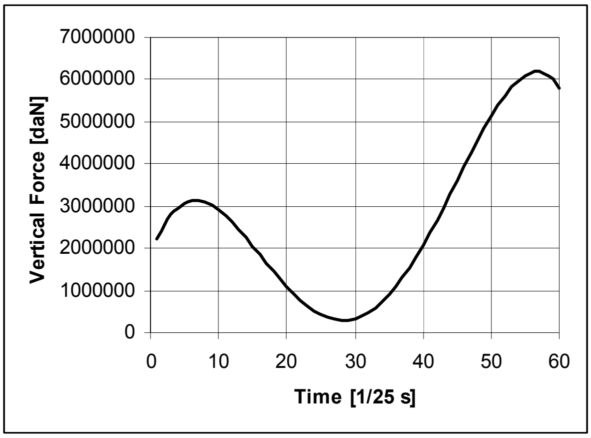
5.2 Dynamics

Using, as unit for the time scale, the interval between successive frames (1/25 s), Figure 7.a shows the calculated values of the vertical reaction, which means the vertical force exchanged between the ground (and already fallen rubble) and the falling building during the fall. It was intuitively expected that the spared part of the bearing section should lose abruptly its bearing capacity against vertical loads, and that the bearing capacity was abruptly resumed upon compaction of the accumulated rubble bed; that means, starting from a finite value (the initial strength of the spared pillar), a no reaction (free fall) interval, followed by an abrupt rise. Calculation based on the cinematic reconstruction of the fall shows a different picture.

The loss of the bearing capacity is not abrupt, but gradual, being distributed in a time interval of perhaps 25 frames: almost free fall conditions, indicated by a very low reaction, last for a very short time lapse, and are stopped by a gradual increase of the vertical reaction, which can be explained as the result of a gradual compression of the rubble and gradual crushing of the impacting body.

If the non abrupt disappearance of the load bearing capacity of the overstressed spared pillars has to be seen as the consequence of a specific strength loss rate of the building material, in our case it has been calculated that the rate is approximately 355 daN/cm^{2}s (this, obviously, is not a general rule, rather a suggestion for further investigations).

Figure 7.b shows the calculated values of the horizontal reaction during the collapse, which has been counteracted mainly by the spared rebars, to a lesser extent by friction. It is curious to observe that, at the end of the collapse, the horizontal reaction becomes negative: the spared rebars and the friction counteract a tendency of the mass to move backwards in most of the falling time, and forward at the end. As to the displacement of the ideal hinge, at the very start it is outside (at right, in the drawings) of the spared pillar, because the pillar initially retains some capability of counteracting bending but, al-most immediately, is transferred within the boundaries of the collapsing pillar, where remains in the critical stage 1, then moves forward, in the closed mouth of the notch.

a) 

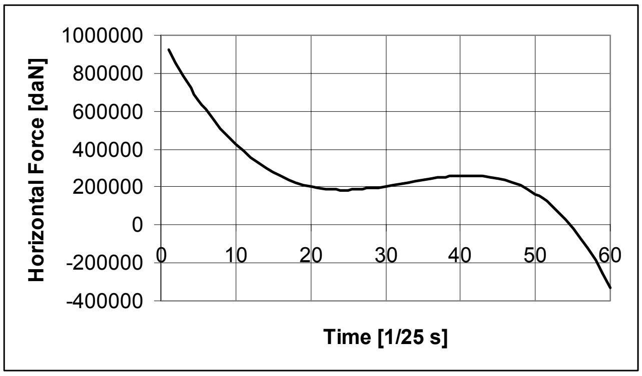
b) 

Figure 7. Calculated values of the vertical (a) and horizontal (b) reactions during the collapse.

6. Conclusions

The behavior of a structure after the destabilization induced by explosive charges is hard to predict, depending on the structure, on the notch geometry and on how the explosive worked: therefore, it is not wise to pretend general rules to emerge from the analysis of hundred cases, not to say from a single case. Strictly speaking, what we learned from the study of a single case is completely useless, being the building already demolished and extremely unlikely that a similar building will be demolished using the same method. The operation here reviewed went out successfully; however, in retrospect, on the basis of the observed behavior of the falling object, some improvement in the design of the mechanical weakening and of the notch could have provided an even better result. Indeed, too much material has been mechanically removed, and the spared sections of the bearing walls adjacent to the back of the building should have been left larger: the stage I, almost vertical fall, lasted too much, with an excessive vertical downward displacement which, paradoxically, could have produced an incomplete collapse: it can be seen that, when the notch closed, the vertical projection of the barycentre was still within the notch area, because rotation started too late; only the already accumulated forward momentum and the crushing of the lip of the notch assured a complete collapse.

Again, in retrospect it went out that the decision of respecting the rebars of the spared walls has been wise: probably, a noticeable unwanted backward movement, and poor control of the rotation, could have take place, in the case of preliminary rebar cutting. Another point which is made evident by the case story is the importance of the original drawings and calculations: these elements are often difficult to retrieve, even for a merely 40 years old building, but are essential. The availability of these documents avoids the dangerous necessity of guessing the safety factors.

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