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Practical methods for increasing the blast resistance of existing buildings

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ABSTRACT

This paper includes the description of the recent Israeli R&D efforts (1991-1993) in researching, developing, testing and building practical strengthening measures for existing buildings, to increase their resistance against explosive effects. The strengthening measures refer to all types of building elements, sensitive to blast loadings, such as windows, doors, light roofs and weak ceilings, as constructed in normal unhardened buildings. The strengthening measures comprise additional means for improving the blast resistance of existing elements, as well as new blast-resistant elements, replacing the existing ones. The strengthening measures cost-effectiveness as well as their implementation are also discussed, in the frame of the Israeli practical experience.

INTRODUCTION

It was repeatedly found that normal buildings are severely damaged by blast loadings from nearby explosions. At larger distances, the most sensitive building components are the normal glass windows, which fail under low blast overpressures. At closer ranges, the doors in the building start failing, followed by light roofs and ceilings. As the blast level increases, normal brick and masonry walls fail and at close ranges the structural elements: columms, beams, etc. begin to "feel" the blast loadings.

Following the lessons learned from observing the damages to many normal buildings in Tel Aviv, during the Iraqui Scud missiles attacks in 1991, the Israeli Home Front Command has embarked on a five-year research and development program (1991-1995) to test, develop and define strengthening measures for existing building components, to increase their blast resistance.

THE TEST PROGRAM

In 1991-1993 the test program included four full-scale tests series, performed in October 1991, April 1992, May 1992 and May 1993. The next full-scale tests are scheduled for June 1994. In the tests performed in 1991-1993, a total of 151 building elements were tested, as described in table no. 1.

TESTS DATE	NUMBER OF EXPLOSIVE CHARGES	NUMBER OF BUILDING ELEMENTS TESTED			
		WALLS	DOORS	WINDOWS	CEILINGS
OCTOBER 1991	24	23	16	49	1
APRIL 1992	10	12	9	27	3
MAY 1992	3	-	-	4	1
MAY 1993	2	1	2	2	1
	TOTAL NUMBER OF TESTED BUILDING ELEMENTS - 151				

Table no. 1 - Full scale tests on strengthening measures for existing buildings

In the June 1994 tests, another 10-15 building elements will be subjected to full-scale explosive charges.

DAMAGE THRESHOLDS OF BUILDING ELEMENTS

The tests results, as well as observed damages to building elements during real attacks, showed that the damage thresholds for different building elements are as follows:

a. Normal 1.0m x 1.0m glass windows, 3-4 mm. thick, failed under blast loadings at scaled distances of 30÷33 $m/kg^{0.33}$ (the scaled distance is the ratio between the explosive charge in meters and the cubic root of the charge weight in kilograms).
Severe injuries to people from glass fragments occur at scaled distances smaller than 15÷18 $m/kg^{0.33}$.

b. Normal wooden doors failed under blast loadings at scaled distances of 7.5÷8.5 $m/kg^{0.33}$.

c. Lignt ceilings and roofs failed under blast loadings and constituted a danger to people at scaled distances of 4.5÷5.5 $m/kg^{0.33}$.

d. Normal brick and masonry walls showed damage thresholds at scaled distauces of 3.0÷3.4 $m/kg^{0.33}$

STRENGTHENING MEASURES FOR EXISTING BUILDING ELEMENTS

Strengthening measures for windows

Temporary expedient strengthening measures for existing glass windows such as:

- Additional "security film", 100 microns thick, on the inner side of the glazing, or
- Additional "safety adhesive bands" on both sides of the glazing,

prevent injuries to people behind the window from glass fragments at scaled distances of 13 $m/kg^{0.33}$.

Providing an inner barrier behind the window, consisting of two layers of ballistic material, brings the injuries threshold to 6 $m/kg^{0.33}$, while the use of four layers of ballistic material reduces the injuries threshold to 4 $m/kg^{0.33}$. However, all the above described temporary strengthening measures do not prevent blast pressures from reaching the internal areas and affecting the people.

New blast resistant glazings were developed and tested, with the following results:

- 7 mm. polycarbonate or 7 mm. layered glass proved efficient in preventing injuries to people at scaled distances of 11 $m/kg^{0.33}$.
- 8 mm. polycarbonate or 9 mm. layered glass proved efficient in preventing injuries to people at scaled distances of 8 $m/kg^{0.33}$.
- 10 mm. polycarbonate or 11 mm. layered glass proved efficient in preventing injuries to people of scaled distances of 6 $m/kg^{0.33}$.
- 12 mm. polycarbonate or 14 mm. layered glass proved efficient in preventing injuries to people of scaled distances of 4 $m/kg^{0.33}$.

It was also found that replacing the existing glass with stronger glazings is only efficient down to scaled distances of about 11 $m/kg^{0.33}$. For lower scaled distance volues, the existing window frames should be replaced by special blast-resistant aluminium or steel frames, into which the stranger glazings can be installed.

Several new innovative blast-resistant windows were developed by different Israeli manufacturers, using the full-scale tests results.

Strengthening measures for doors

Strengthening of existing wooden doors, opening inwards, in the direction of the blast pressares, was only feasible for scaled distances of about 8 $m/kg^{0.33}$, using different additional steel bars and locking devices. These measures still did not prevent blast leakage behind the door.

For lower scaled distance values, the existing doors should be replaced by new metal blast-resistant doors, opening outwards. Different types of metal security doors were developed and found efficient down to scaled distances of 6 $m/kg^{0.33}$. Strenger metal blast-resistant doors were further developed and proven efficient for scaled distauces of 4 $m/kg^{0.33}$.

Strengthening measures for light ceilings and roofs

Two types of innovative strengthening measures were developed for strengthening existing light ceilings and roofs:

- an additional inner barrier made of thin (0.8-1.2mm) metal plates.
- an additional inner cover made of ballistic material.

The above strengthening measures proved effective at scaled distances of 2.7 $m/kg^{0.33}$.

Strengthening measures for walls

Three types of strengthening measures for existing walls were developed and tested:

a. Additional strengthening measures on the inner face of the existing wall.

b. Additional strengthening measures on the outer face of the existing wall.

c. Replacing the weak existing wall by a new wall.

The following wall strengthening measures were found to be effective in preventing injuries to people at scaled distances of 2.1 $m/kg^{0.33}$:

- Additional ballistic material cover on the inner face of the wall.
- Additional internal 8 cm thick silicate blocks on the inner face of the wall.
- Additional metal panels on the inner face of the wall.
- Additional concrete layer on the inner face of the wall.
- Additional external metal panels at a small distance from the outer face of the wall.

The most effective wall strengthening measures which would prevent injuries to people at scaled distances of 1.6 $m/kg^{0.33}$ are:

- Additional concrete layer on the inner face of the wall.
- Additional wood-cement bricks filled with concrete, built on the inner side of the wall.

The following "new" walls could be used to replace the weak existing walls:

- Reinforced concrete panels - prefabricated - with adequate connections.
- Double concrete wall with internal air gap.
- Wood - cement bricks filled with concrete.

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Summary of the present research and developmment activities

The effectiveness of the various strengthening measures developed during the period 1991-1993 is summarized in table no. 2.

Strengthening measure	Damage threshold for the existing building element ($m/kg^{0.33}$)	Damage threshold for the strengthened building element ($m/kg^{0.33}$)
Strengthening the existing window glass	33	13
Changing the existing window glass with stronger glazing materials	33	11
Replacing the existing window with a new blast-resistant window	33	4
Replacing the existing wooden door with a new blast-resistant door, opening outwards	8	4
Adding an additional barrier beneath light ceilings/roofs	5	2.7
Strengthening existing walls by different internal or external measares	3.2	2.1
Replacing existing walls by new innovative walls	3.2	1.6

Table no. 2 - Effectiveness of the various new strengthening measures

DEFINING THE OPTIMAL COST - EFFECTIVE STRENGTHENING MEASURES

In order to define the optimal cost-effective strengthening measures, the analythical computer-aided methodology called SEPHRA (SE curity, Protection and Hardening Risk Analysis), developed by the author, can be used.

SEPHRA includes five major stages of analysis:

a. <u>Threat analysis</u>, including the consideration of the probabilities of hit for the defined threats as well as the installation characteristics.

b. <u>Damage analysis</u>, resulting in quantitative estimation of the expected damages to structures, equipment, etc. as well as possible injuries to personnel.

c. <u>Risk assessment</u>, with the final result expressed as a risk level for the structure/facility.

d. **Countermeasures cost-effectiveness analysis**, consisting of assessing the reduction in the risk level by different hardening/strengthening measures related to the respective cost of the measures, and

e. **Countermeasures optimization** - leading to the definition of the optimal countermeasures.

The main stage of SEPHRA is the damage analysis in which all our practical experience and knowledge as well as the best engineering judgement are used to quantify the expected number of injuries for people in an existing stucture, due to blast effects. The flowchart of the blast effects damage analysis is presented in figure 1.

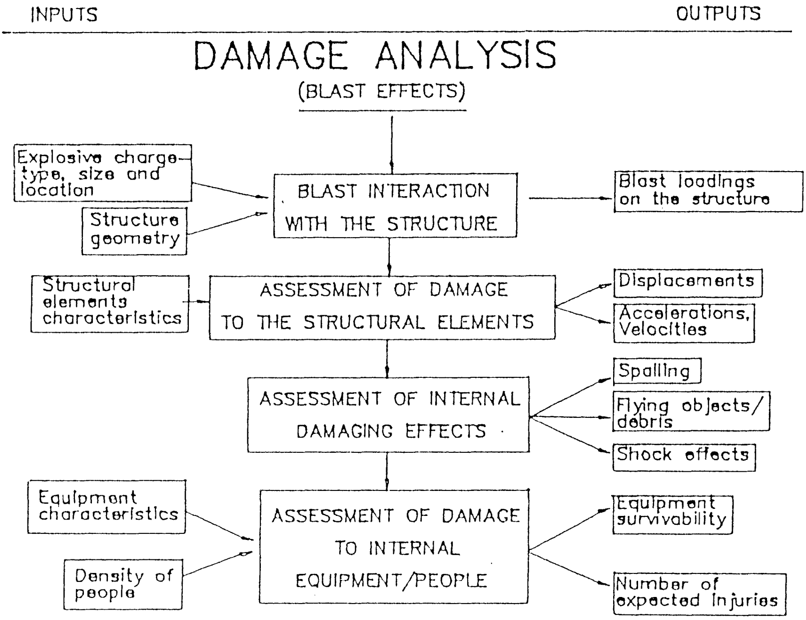

Figure 1. Flowchart of the blast effects damage analysis

Using stages a) b) and c) af SEPHRA for an existing building/installation, the risk level can be assessed, in terms of expected injuries to people inside the building/installation. Then, in SEPHRA stage d), various strengthening measures, such as those presented in this paper, cam be analysed, each measure with it's cost and risk reduction. SEPHRA stage e) summarizes the whole analysis findings in a diagramatic format, ploting the risk against the cost of the strengthening measures, as shown in figure 2.

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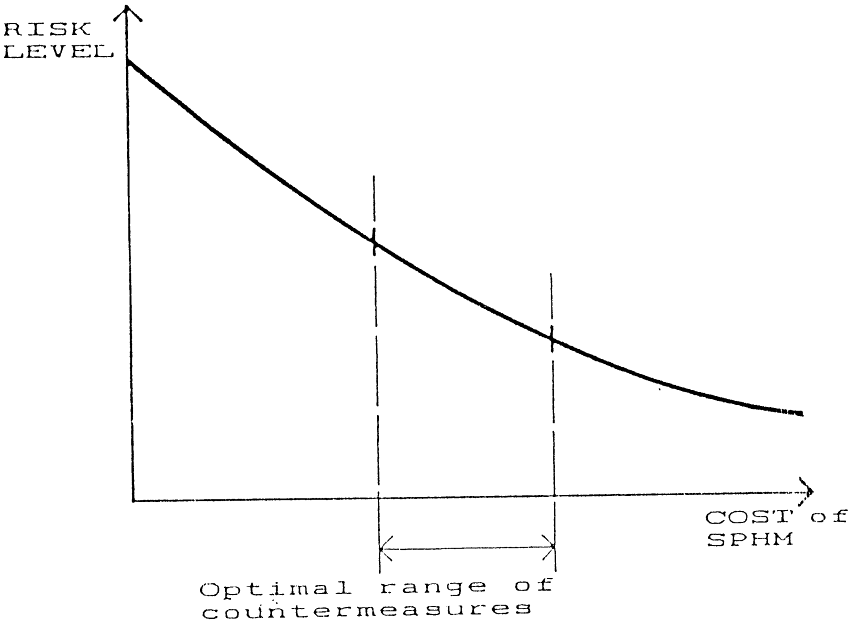

Figure 2 - Deciding on the optimal security, protection and hardening measures (SPHM)

The optimal set of strengthening measures can be established by using the diagram presented in figure 2.

IMPLEMENTATION OF STRENGTHENING MEASURES IN EXISTING BUILDINGS

The implementation of strengthening measures in existing buildings has started in Israel in 1991 and is ongoing now.
The types of strengthening measures described in this paper have been already implemented in existing buldings, with optimal cost-effectiveness.

CONCLUSION

During the period 1991-1993 numerous strengthening measures for windows, doors, light ceilings/roofs and walls of existing buildings have been developed, tested and implemented in Israel.

These strengthening measures are cost-effective, innovative and will reduce considerably the rate of injuries in case of future attacks.

Functional as well as cost considerations should be added to the protection aspects when choosing the optimal solutions.

The research and development of further innovative strengthening measures for existing building elements is presently continuing in Israel; the next full-scale tests are scheduled for June 1994.