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DESIGN CRITERIA FOR A CONTROLLED DEMOLITION (IMPLOSION)

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ABSTRACT: For an uncontrolled demolition (terrorist attack) explosives are detonated external to a structure primarily but not always. On occasions the terrorist attack is internal to a structure which can also cause the building to collapse. With a controlled demolition (implosion), explosives are always used internal to a building. A building is imploded within its' own design footprint but because of adjacent structures inhibiting it's fall the building might have to be imploded and collapsed outside of its footprint. An oddity is the implosion of a chimney stack. Chimney stacks because of the physics involved can, whilst collapsing, break into two separate pieces which causes concern as the trajectory of fall can then become uncontrollable. Several conditions need to be addressed prior to a demolition as follows:

- Is space available to accommodate the debris pile loose volume generated by the implosion?
- Is the minimum charge weight of explosives being used?
- Will the falling structure cause fragments to impact adjoining structures or can the fragmentation be contained?
- Has consideration been given to dust control?
- After considering structural details of the building does the structure lend itself to collapse through implosion or should the building be demolished by mechanical means? and
- Does the demolition by implosion prove to be more economical and safer than mechanical means?

A successful demolition occurs if the conditions above are appropriately addressed and executed. The alternative is to not follow the appropriate conditions and so face three failures that have occurred over the last 20 years in Australia.

Keywords: Implosion, Collapse, Fragmentation, Ground shock, Dust cloud

1. IINTRODUCTION

Implosion is defined as the designed collapse of a building using explosives within its own footprint [1] but it is necessary to understand what exactly progressive collapse is and what if anything the difference is between a progressive collapse [2] and an implosion. Progressive collapse is where local failure of a primary structural elements leads to the collapse of adjoining members which in turn results in further collapse meaning the collapse is disproportionate to the original cause. It is also a chain reaction of failures following damage to a relatively small portion of a structure and so can be defined by two general methods. Those methods are as follows;

- indirect design that considers the implicit resistance to progressive collapse [3] by the provision of minimum levels of strength, ductility and continuity, and
- direct design that considers the explicit resistance to progressive collapse through the alternate path method [4] which allows firstly for local failure to occur but provides for alternative load paths for damage to be minimized thus averting major collapse and secondly for the specific local resistant method for extra structural strength to resist major failure.

2. CONTROLLED DEMOLITION PREPARATIONS

Preparations are not only for the start of the implosion [5] process but also for action at the end of the process.

2.1 PRE-WEAKENING

Pre-weakening involves the removal of all non-loading bearing walls, fixtures and fittings, mechanical equipment, plumbing and piping (electrical, water, sewage and communications), stairways and facades including all glazing from the building leaving intact the basic structural elements such as columns, beams and floors. In columns that are to be drilled and loaded with explosives many that contain circular or rectangular steel stirrups or spirals that are tightly pitched must be exposed and cut. Shear walls [6] need to be pre-weakened mechanically by the removal of the concrete matrix around the steel reinforcing to make in effect plastic hinges that will operate to assist collapse when the implosion is activated.

2.2 Drilling for Explosives Placement

The key structural element that facilitates collapse is the column and so all columns are drilled to take explosives. Placing explosives on the face of columns would lead to the explosive shock wave dissipating away from the column whereas if the explosive charge [7] is placed into and central to the column the full extent of the shock wave produced by the detonation is impacted on the column. When explosives are placed in the drill holes for the pressure from detonation to be confined stemming [8] must be provided using small bags filled with sand or with high density foam.

2.3 Placement of Explosive Charges

.Water-gel explosives and explosive emulsions have a higher velocity of detonation (VOD) of 4000m/s which is higher than for another commercial explosive ammonium nitrate (ANFO) [9] with a VOD of 3600m/s. Gelignite a combination of nitroglycerine and nitrocellulose in a base of wood pulp with sodium potassium nitrate and dynamite are also other common explosives used in an implosion both of which because of their chemical components are stable to handle. PETN [10] or pentaerythritol tetranitrate another military high explosive with a VOD of 3500m/s and insoluble in water is also used primarily in the detonating chord so as to detonate the explosive used to form plastic hinges in the RC. Explosive linear cutting charges are used to cut steel structural elements. For steel cutting charges they are primarily an RDX [11] or cyclotrimethylene trinitramine military high explosive with a VOD of 8750m/s. RDX is placed in a chevron shaped sheath of malleable metal such as copper and once detonated against the steel structural element generate cutting pressures more than 21,000MPa via a method called the “Monroe” effect.

2.4 Explosive Blast Design Formulas for use in Controlled Implosions

Military and civilian formula can be used during an implosion process to form plastic hinges in walls particularly shear walls, columns bridge abutments etc. to assist collapse but there are advantages and disadvantages with each of the formula chosen. All have been tested in the field and will produce a plastic hinge by cracking the concrete matrix around the reinforcing bars thus shifting predominately compressive loads onto the steel resulting in steel yielding.

2.5 Military Formula

For the military the use of explosives is not normally to form plastic hinges in primarily RC targets as well as other materials (Tables 1&3) but to demolish or breach targets such as walls, piers and abutments and normally without any detailed idea of whether the target is reinforced or not nor the concretes tensile strength (MPa). The formula he chooses to use may be for a mandated explosive (e.g., C4, TNT) without the ability to choose an alternative explosive. C4 [12] is an American plastic explosive whilst P4 [12] is the British and Australian equivalent.

2.5.1 Breaching Charges

The following formula, Tables and Figures show those used by the US Army Corps of Engineers in a Field Manual [13] to undertake demolition and breaching of targets [14]. The formula used to determine the size of the explosive charge required to breach concrete, masonry, rock or similar material is in Eq. (1):

$$
\begin{aligned}
&P = R^3 KC \\
&where: \\
&P = \text{TNT required (lbs)} \\
&R = \text{Breaching radius (ft)} \\
&K = \text{Material factor which reflects} \\
&\quad \text{hardness and mass of the material} \\
&\quad \text{to be demolished (Table 38)} \\
&C = \text{Tamping factor which depends} \\
&\quad \text{on the location and tamping} \\
&\quad \text{of the charge (Figure 218)}
\end{aligned} \qquad (1)
$$

Concrete is always assumed as being reinforced and masonry is first-class unless the exact condition and construction of target materials is known. A charge tamped with a solid material (such as sand or earth) is not considered as fully tamped unless the charge is covered to a depth equal to or greater than the breaching radius. The water depth must be greater than the radius to use 1 as C (Fig.1 and Table 2). Table 2 shows the placement of breaching charges for reinforced concrete using C4 instead of TNT [15] whilst Table 1 provides conversion factors when other types of materials are attacked.

Table 1 Material factor (C) for breaching charges (FM 3-34.214)

MATERIAL	R	K
Earth	All values	0.07
Poor masonry Shale Hardpan Good timber Earth construction	Less than 1.5m (5ft) 1.5m (5ft) or more	0.32 0.29
Good Masonry Concrete block Rock	0.3m (1ft) or less Over 0.3m (1ft) to less than 0.9m (3ft) 0.9m (3ft) to less than 1.5m (5ft) 1.5m (5ft) to less than 2.1m (7ft) 2.1m (7ft) 0r more	0.88 0.48 0.40 0.32 0.27
Dense concrete First class masonry	.3m (1ft) or less Over 0.3m (1ft) to less than 0.9m (3ft) 0.9m (3ft) to less than 1.5m (5ft) 1.5m (5ft) to less than 2.1m (7ft) 2.1m (7ft) 0r more	1.14 0.62 0.52 0.41 0.35
Reinforced concrete (factor does not consider cutting steel)	.3m (1ft) or less Over 0.3m (1ft) to less than 0.9m (3ft) 0.9m (3ft) to less than 1.5m (5ft) 1.5m (5ft) to less than 2.1m (7ft) 2.1m (7ft) 0r more	1.76 0.96 0.80 0.63 0.54

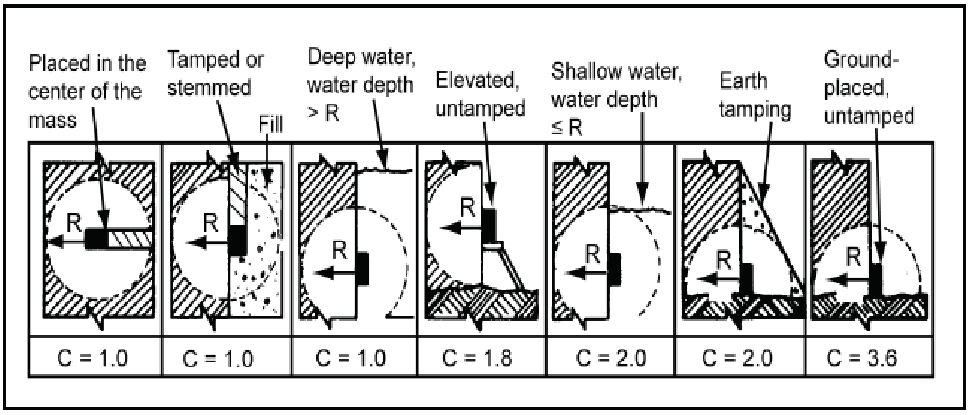

Fig. 1 Tamping factor for breaching charges (FM 3-34.214)

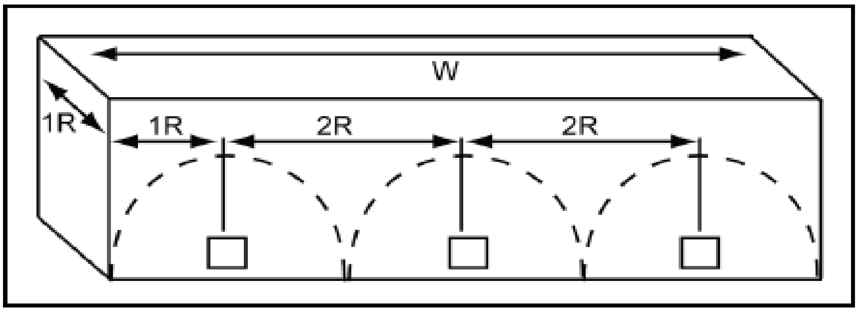

Fig. 2 Charge placement in piers and walls (FM 3-34.214)

Table 2 Breaching C4 explosive charges for reinforced concrete (FM 3-34.214)

	Placement Methods						
	Placed in the center of the mass	Tamped or stemmed / Fill	Deep water, water depth > R	Elevated, untamped	Shallow water, water depth ≤ R	Earth tamping	Ground-placed, untamped
							
	C = 1.0	C = 1.0	C = 1.0	C = 1.8	C = 2.0	C = 2.0	C = 3.6
Reinforced Concrete Thickness (ft)	***Packages of M112 (Composition C4)***						
2.0	1	5	5	9	10	10	17
2.5	2	9	9	17	18	18	33
3.0	2	13	13	24	26	26	47
3.5	4	21	21	37	41	41	74
4.0	5	31	31	56	62	62	111
4.5	7	44	44	79	88	88	157
5.0	9	48	48	85	95	95	170
5.5	12	63	63	113	126	126	226
6.0	13	82	82	147	163	163	293
6.5	17	104	104	186	207	207	372
7.0	21	111	111	200	222	222	399
7.5	26	137	137	245	273	273	490
8.0	31	166	166	298	331	331	595

Table 3 Conversion factor for materials other than reinforced concrete (FM 3-34.214)

MATERIAL	CONVERSION FACTOR
Earth	0.1
Ordinary masonry Hardpan Shale Ordinary concrete Rock Good Timber Earth construction	0.5
Dense concrete First class masonry	0.7

$$N = \frac{W}{2R} \tag{2}$$

where :

N = Number of charges (if N is less than 1.25 use 1 charge; if N is 1.25 but less than 2.4 use 2 charges; if N is equal tp or greater than 2.5 round up to the nearest whole number.)

$$\frac{d}{h} = 0.919\ln\left(\frac{Qk\rho_x}{h^3\sigma\rho_c}\right) \tag{3}$$

where:

d = Hole diameter (m)

h = Slab thickness (m)

Q = Explosive charge weight (kg)

k = Explosive energy (J/kg)

ρ_x = Explosive density (kg/m^3)

σ = Concrete strength (Pa)

ρ_c = Concrete density (kg/m^3)

2.5.2 Number and Placement of Charges

Equation (2) is used to calculate the number of charges required for demolishing piers slabs or walls. Piers and walls offer limited locations for placing explosives (see Fig.2). Unless a demolition chamber space is intentionally provided in a structure for the emplacement of explosive charges is available, charges are placed against one face of the target. Placing a charge above ground level is more effective than placing one directly on the ground. When the demolition requires several charges to demolish a pier, slab or wall and elevated charges are to be positioned the charges should be distributed equally no less than one breaching radius high from the base of the target. For piers, slabs or walls partially submerged in water, charges should be placed at a distance equal to the breaching radius and below the waterline.

2.5.3 Disadvantages

- Tables only allow for the use of one type of explosive.
- No conversion factors are provided if different types of explosive are chosen with a different velocity of detonation (VOD) or density.
- No account has been made for size and type of steel reinforcement or its exact placement (no geometry provided) within the RC target.
- Although “ordinary” and “dense” concrete is mentioned it is unlikely these descriptions cover the new types of concretes such as [16], ultra-high (UHS) strength concretes [17] and fiber reinforced (FRC) [18] concretes incorporating steel, fiberglass and polymer fibers.
- Conservative aspects of the blasting formula will lead to much larger explosive charge weights being used.
- The explosive charge is placed at the center of mass in a wall or a column to form the plastic hinge and collapse, so the use of contact charges is far from ideal to achieve the same outcome.
- Equation (2) will certainly crack and dislodge the concrete matrix around the reinforcing, but the reinforcing will remain thus requiring linear cutting charges to remove the reinforcing steel.

2.5.4 Advantages

- Standardization or limited choice of formula being provided to the military engineer provides for less likelihood of error in a field environment, a greater likelihood of success and a much faster demolition process (time is critical in military environments).
- Military engineers of many western countries not only use the same formula but use them on a regular basis thus leading to familiarity of use.

2.6 Civilian Formula

2.6.1 Lonnqvist (Swedish) Formula

Forsen in 1990 [19] considered wall breaching in a series of experiments he conducted to determine a relationship of the charge weight of the explosive and the hole diameter formed on direct contact detonation of the explosive against reinforced concrete targets. He used hemispherical, spherical, cubical and cylindrical charges. In 1993, Lonnqvist extended Forsens’ research to included additional parameters and developed a dimensionless charge weight to hole diameter relationship as in Eq. (3). The level of damaged sustained to a RC wall from such a contact charge, is a function of the charge weight (kg), distance from the charge to the wall (stand-off) and the wall thickness with spalling from the rear of any wall being an important consideration. The processes occurring at the target are decreased with increased stand-off distance such as smaller cracks and less surface cratering, less wall deflection and significant racking, less spalling to the rear surface of the wall, penetration and lastly less perforation and extreme bending of the reinforcement.

2.6.1.2 Disadvantages

- Equation (3) doesn’t mention the steel reinforcement that will be exposed when a contact charge is detonated thus requiring the use of a linear charge to cut the steel.
- Slab thickness of the target will be set but the hole diameter required to be breached will have to be stated or calculated in advance of the detonation.
- with a specific charge weight and type of explosive detonated.

2.6.1.3 Advantages

- Equation (3) is far more flexible than military formula in that it caters for the use of different types of explosives meaning that the explosive density and explosive energy of the explosive can be inserted into the equation, so it is not tied to one type of explosive as is the case with military formula.
- Equation (3) allows for differing concrete strengths and density which is an advantage as more worldwide

- infrastructure is being constructed using the new types of concretes such high strength and ultra-high strength concretes.
- Military formula is conservative which leads to larger explosive charge weights being used whereas the flexibility of the Lonnqvist equation leads to far smaller cost-effective explosive charge weights being detonated.
- Equation (3) can be used to determine the breached hole diameters for differing charge weights of differing explosives.

2.6.2 Kraus (German) Formula

The formula [7] in Eq. (4) is somewhat crude in that it lacks the detail of the above two formula with only the hole diameter resulting from a breach being designated.

2.6.2.1 Disadvantages

- It is assumed (see military formula) the tamping factor in this case varies from a =1.0 to a = 4.5.
- Equation is less flexible than the other two formulas above.
- Using TNT equivalence, one must calculate the charge weight of an explosive chosen to be used once the TNT charge weight is specified.
- Equation only applies to concrete with no conversion factors provided for other materials.

2.6.2.2 Advantages

- A simple equation easy to use in a preliminary design to arrive at an explosive charge weight for a specific breach radius.

2.6.3 Gustafsson (Swedish) Formula

This formula assumes that the disintegration or demolition of mass concrete follows rules designed for rock excavation in which powder (explosive) factor and hole spacing are sufficient for design. The powder factor is the explosive energy per volume (kg/m^3) of the fragmented material (concrete) and is defined as the explosive charge weight per volume of the concrete. Walls (shear walls) [20] and columns can be demolished providing shot parameters in Table 5 are followed

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Table 4 Specific charge (per unit volume) for disintegration of massive concrete

LARGEST WIDTH (m)	DEPTH OF HOLE (m)	HOLE SPACING (m)	NUMBER OF ROWS	CHARGE PER HOLE (kg)
0.30	0.20	0.30	1	0.05
0.40	0.30	0.30	1	0.10
0.50	0.40	0.35	2	0.085
0.60	0.45	0.35	2	0.125
0.70	0.55	0.35	2	0.17

Table 5 Hole geometry and loading for disintegration of concrete columns

TYPE	SPECIFIC CHARGE^a (kg/m^3)	HOLE SPACING^b (m)
Non-reinforced concrete of poor quality	0.25 – 0.30	0.80 – 0.90
Non- reinforced concrete of good quality and material strength	0.30 – 0.40	0.75 – 0.90
Reinforced concrete with heavy reinforcement	0.80 – 1.00	0.5– 0.60
Extra powerful reinforced concrete of military type	1.50 – 2.0	0.40 – 0.50 0.50 – 0.55

Distributed equally along holes with pre-packaged explosive in thin tube units with explosives 0.32 kg of explosive per meter of hole (depth)^a. Square pattern^b.

2.6.3.1 Disadvantages

- This is another formula that is not specific as to the concrete strength of the structure being demolished.
- Quality of the concrete must be assumed.
- No geometry of the structure to be demolished is capable of being considered within either Table 3 or Table 4.

2.6.3.2 Advantages

- This is the ideal formula for attempting to form plastic hinges at regularly intervals along a shear wall to facilitate collapse during an implosion.
- Formula provides not only the charge per hole but the distribution of the explosive along the depth of the hole if necessary.
- The specific charge specified in Table 5 is in fact the density (kg/m^3) of the explosive to use thus identifying the type of explosive detonated.

2.6.4 Savytskyi, Nikiforova and Grosman (Russian) Formula [21]

Concentrated contact charges are considered to demolish a structure (controlled implosion) and concrete columns with the charge weight of explosives being determined from the geometry of the explosives needed for the outer surface of the column for at least three quarters of the perimeter of the column. Concentrated contact charges for the demolition of reinforced concrete columns with a width of not more than twice the thickness is calculated as per Eq. (5).

$$M = R^3 ac \tag{4}$$

where:
M = Explosive charge (kg TNT)
R = Effective radius (m)
a = Tamping factor (4.5 for an untamped charge)
c = Resistance factor depending on R

\`a	≤ 1.5 m	≤ 2.0 m	≤ 3.5 m	> 3.5 m
c	6	5	4	4

If columns are provided with special outer reinforcement such as spiral reinforcing in addition to normal reinforcement cages Eq. (5) is increased by a factor of 6 to form Eq. (6).

2.6.4.1 Disadvantages

- Equation (5) only suitable for a column with width no greater than twice its thickness.
- No information provided for a column that does not fit these criteria.
- Formula does not provide information as to how to accommodate the implosion and placement of explosive charges or hole spacing when confronted with a shear wall where its width is much larger than twice its thickness.
- Formula is not specific as to the type or difference of an explosive charge
- placed internal to the column or on the outside as a contact charge.
- Formula makes no specific reference to other materials other than concrete.

2.6.4.2 Advantages

- Equations (5) & (6) cater for all types of explosives.
- Simple equations with only limited data required to calculate an explosive charge weight.

$$C = ABR^3 \tag{5}$$

where:
C = Charge weight (kg)
A = Factor depending on t he properties of undermining material and explosives used ($A = 20$)
B = Factor depending on the location of the charge (B=9)
R = Radius of destruction (m)

$$C = 6ABR^3 \tag{6}$$

where:
C = Charge weight (kg)
A = Factor depending on the properties of undermining material and explosives used ($A = 20$)
B = Factor depending on the location of the charge ($B = 9$)
R = Radius of destruction (m)

2.7 PLACE SEISMOMETERS

In Australia ground vibrations (ground shock) of no more than 25mm/s are considered acceptable to impact on adjoining structures [22]. If the ground shock is less than the value, the damage should be negligible. When considering whether damage has been sustained to adjoining structures as a direct result of the implosion the exact strain levels structural elements within adjoining buildings had previously been subjected to must be known.

2.8 PLACE CONTAINMENT FRAGMENTATION BARRIERS

Structural elements containing explosives are wrapped firstly in steel mesh and then in a polymer or geo-fabric to contain all fragments generated by the explosion. To cater for this eventuality and so mitigate against any damage to adjoining structures or individuals caught nearby barriers such as shipping containers, bales of hay or even earthen mounds are positioned to catch this overflying debris. Control of dust cloud [23] according to Occupational Health and Safety Australia (OHSA) dust particles of size ranging from 0.001 to 0.1 mm (1 to 100 microns) pose a threat to health when airborne thus reducing visibility and possibly resulting in damage to the tissues of the lungs. Harmful dust including silica and asbestos is that which has a particle size of less than 5 microns in size or 0.005 mm.

2.9 COLLAPSE FOOTPRINT

The footprint of the collapse is determined primarily by the trajectory of fall of the building. The key to a controlled trajectory is to ensure that collapsing building is tied together enough for its collapse to be controlled. Columns at the front of a building collapsed by using explosives can be connected via steel wire rope to columns at the rear of the structure so that as the building collapses the collapsing columns at the front pull on the ones at the back thus providing the necessary directionality to the collapse.

2.10 EXPLOSIVE POSITIONING IN STEEL AND CONCRETE STRUCTURES

Implosion concentrates on the columns on the lower floors of the structure as if demolished first they will release the greater potential energy that will ultimately facilitate collapse. The lowest floor is normally fitted first then the floors above are fitted out successively further apart up the building's height. The more gravity that is used during the implosion process the greater the debris is pulverized and so more easily handled during its removal. Another reason for varying the blast floor spacing is that with all tall buildings the floors at the top of the building are of lighter construction meaning that the floors below carry less weight, but nevertheless more kinetic energy is released during the collapse process because of their height above ground in relation to other floors of the building. With RC structural elements, the aim is to detonate an explosive within the column thus forming a plastic hinge as the explosive shatters the concrete matrix away from the steel reinforcing causing the compressive load carried by the column to shift to the reinforcing steel that in turn yields under load so collapsing the column. Successive collapse of columns in rows on floors or in sequence from the front of the building to the back of the building gives trajectory or direction to collapse. Two cutting charges are strapped diagonally to the column and detonated causing a wedge of steel being removed. To assist in driving the steel wedge out laterally from the column an assisting C4 small charge is applied to the clean flange of the column and detonated along with the cutting charges.

2.11 COLLPASE DETONATION TIMING SEQUENCE

The basic tenant that applies to a collapse timing sequence is that for the basic physics of freefall to apply (Table 6 parameters) it must be understood that structures rarely accelerate at the freefall rate because of structural elements still standing and so resisting freefall. For an implosion the closer the collapse resembles freefall the more likely the building will progressively collapse. For freefall during progressive collapse of a building the kinematic equations of motions are applicable as in Eq. 7 & 8 below. If all floors strike the ground at once then the ground shock experienced will be high and, probably, exceed the maximum value or Peak Particle Velocity (PPV) allowed by legislation (i.e. 25mm/s). Mayne developed a general equation with two further equations from field experiments that can be used to calculate PPV as follows. Equation (11) is the general equation whilst Eq. (12) provides a PPV considered as a conservative upper limit for silty sands, sandy clay, rubble and fill. Eq. (1) was calculated so as engineers could then calculate the true vector sum (TVS) of the tri-axial components of a vibration and a single maximum component.

AS2187.2 gives guidance in relation to higher acceptable limits in Australia for PPV's and they are a:

- Frequency-based limit up to 50mm/s to control the threshold of damage.
- Ultimate limit of 100mm/s for control of damage to unoccupied steel or concrete structures.
- Human comfort limit of 5mm/s (long term) and 10mm/s (short term) for
- sensitive receivers, houses, schools, libraries, theatres etc.
- Human comfort limit of 25mm/s for non-sensitive receivers in industrial and commercial buildings.

$$t = \sqrt{\frac{2d}{g}} \tag{7}$$

where t is the time of fall distance in seconds
d is the fall distance in metres
g is the acceleration due to gravity equal to $9.81 m/s^2$

$$v = \sqrt{2gd} \tag{8}$$

where v is the velocity in m/s

$$PE = mgh \tag{9}$$

where PE equals the potential energyin Joules (J)
m equals the mass (kilograms)
g gravitational acceleration $(9.81 m/s^2)$
h equals the hight in mteres (m)

note: 1Joule equals 1 $kg\, m^2/s^2$

$$KE = \frac{1}{2} m v^2 \tag{10}$$

where KE equals the kinetic energy in Joules (J)
v equals the velocity (m/s)

$$\text{PPV} = K\left(\frac{d}{\sqrt{E}}\right)^n \tag{11}$$

where $K$is intercept ordinate
n is slope or attenuation rate (constant 1.0 to 2.0)
d is the distance
E is energy
$\frac{d}{\sqrt{E}}$ is scaled distance

$$\text{PPV} \le 92\left(\frac{\sqrt{WH}}{d}\right)^{1.4} \tag{12}$$

where W is weight in tonnes
H is the height in metres (m)
d is the distance in metres (m)

$$\text{PPV} \le 70\left(\frac{\sqrt{WH}}{d}\right)^{1.4} \tag{13}$$

where W is weight in tonnness
H is the height in metres (m)
d is the distance in metres (m)

Table 6 Kinematic Parameters for a Building Collapse

FLOOR	d	$\frac{2d}{g}$	$\sqrt{\frac{2d}{g}} = t$	v
	(m)	(sec)		(m/s)
6th	18	3.669	1.915	18.79
5th	15	3.058	1.748	17.15
4th	12	2.446	1.563	15.34
3rd	9	1.834	1.354	13.28
2nd	6	1.223	1.105	10.84
1st	3	0.611	0.781	7.67
GROUND	0	0	0	0

2.12 ADVANTAGES AND DISADVANTAGES OF DIFFERENT BUILDING TYPES

Some buildings are better suited to the implosion technique than others because they have problematic structural elements within the structure which are not predisposed to produce a successful implosion. Jointed precast structures [24] once imploded separate and collapse quickly thus making trajectory control difficult to achieve. Progressive collapse in these structures is not difficult although current designs attempt to mitigate collapse by employing more robust joint connections thus making implosion a more difficult proposition because the more robust joints are less likely to release potential energy quickly inhibiting progressive collapse.

2.13 CONTROLLED DEMOLITION DESIGN CRITERIA

Those criteria that are applicable to the implosion design process are;

- use only minimum charge weight (kg) of explosives to successfully achieve the implosion,
- remove all necessary structural elements to lighten the structure and facilitate collapse,
- minimize ground vibrations to eliminate damage to adjoining structures,
- minimize and control the spread of the cementitious dust cloud,
- minimize or eliminate fragmentation of any kind,
- designate a designed footprint to collapse the structure within,
- design for a debris pile of suitable dimensions to facilitate its removal,
- designate suitable safety distances to eliminate any casualties if fragmentation is produced, and
- police and maintain safety distances during the firing sequence.

2.14 CONTROLLED DEMOLITION DESIGN STRATEGY

As safety is paramount with a controlled demolition the following strategies apply:

- at the outset of the design obtain all drawings available to fully understand the structural components of the building,
- liaise with local authorities and police,
- document in detail the implosion and its benchmarks and all personnel on site,
- document before and after the implosion all structural defects,
- abide by all government legislation in relation to ground shock, cementitious dust control and safety distances,
- utilize instrumentation to monitor and record noise levels, ground shock and air quality, and
- provide for good site communications to all parties involved.

2.15 CONCLUSION

There have been several failures one resulting in a casualty from fragmentation but, as development in Australian cities gains pace to cater for the increase in population this will no doubt lead to the use of implosions. Implosion use will increase within Australia if the following points are actioned by respective Federal, State and Local Governments and the engineering fraternity:

- the production and publication of an Australian Standard for Controlled Demolitions,
- suitable accreditation or licensing for those already involved with implosions (Australian State shotfirer licenses are inadequate in the case of implosions),
- suitable accredited training and licensing for engineers to be involved in implosions,
- provide research funding for implosion particularly into ground shock, cementitious dust control, fragmentation and demolition of commercial chimney stacks that because of the physics involved in their collapse tend to break into two during collapse.

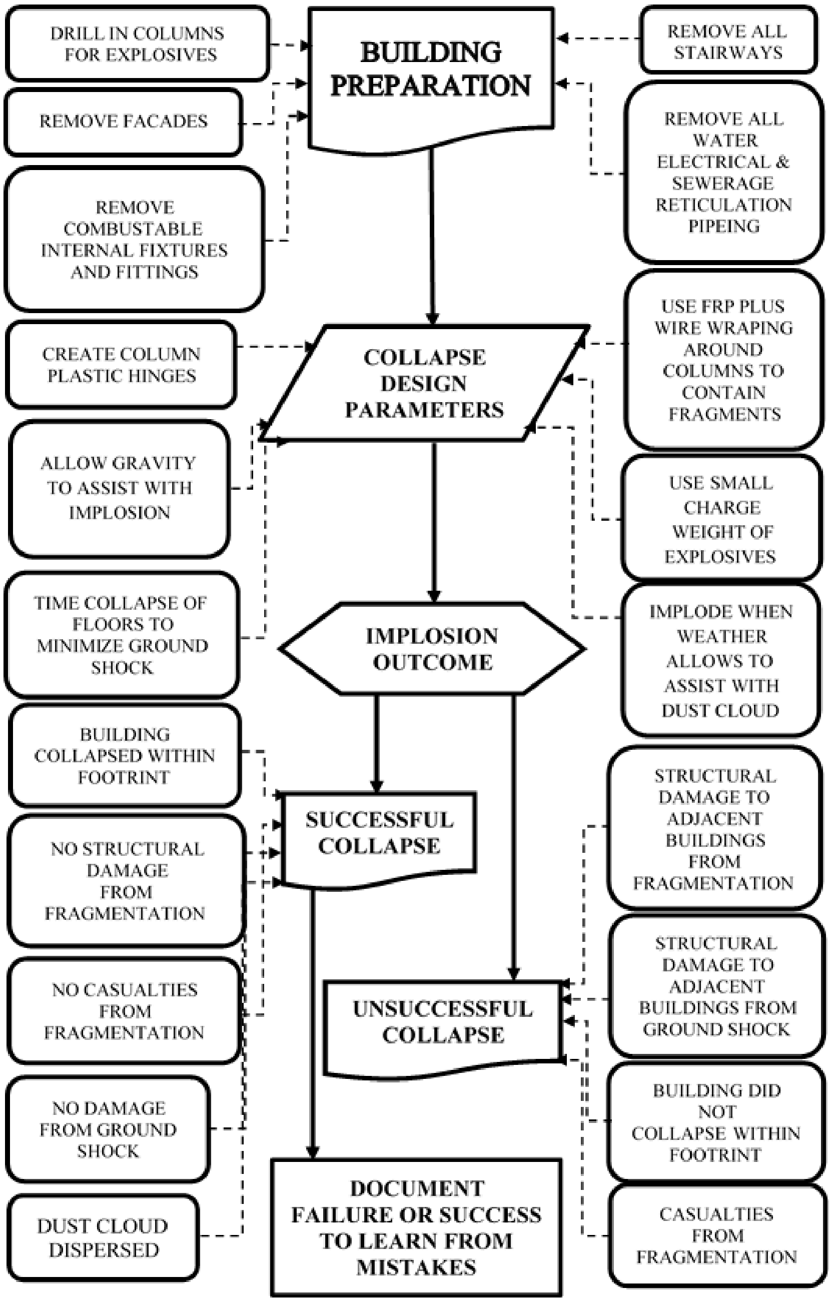

Fig. 3 Controlled demolition design process flowchart

3. REFERENCES

[1] Ji-liang J. The Parameters of Blasting Cut for Directional Collapsing of Highrise Buildings and Towering Structures [J]. Engineering Blasting. 2003;4:001.

[2] Morey MPK, Satone S. Progressive Collapse Analysis Of Building. Progressive. 2012;2(4):742-5.

[3] Shi Y, Li Z-X, Hao H. A new method for progressive collapse analysis of RC frames under blast loading. Engineering Structures. 2010;32(6):1691-703.

[4] McKay A, Marchand K, Diaz M. Alternate path method in progressive collapse analysis: Variation of dynamic and nonlinear load increase factors. Practice Periodical on Structural Design and Construction. 2012;17(4):152-60.

[5] Loizeaux M, Osborn AE. Progressive Collapse—An Implosion Contractor’s Stock in Trade. Journal of Performance of Constructed Facilities. 2006;20(4):391-402.

[6] Clayton PM, Berman JW, Lowes LN. Seismic design and performance of self-centering steel plate shear walls. Journal of Structural Engineering. 2011;138(1):22-30.
[7] Meyer R, Köhler J, Homburg A. Explosives: John Wiley & Sons; 2016.
[8] Shann PC. Stemming arrangement and method for blast holes. Google Patents; 2002.
[9] Nataraja Moorthy T, Hamdan HHB, Phang CC. Identification of Fuel Oil in Absorbent and Non-absorbent Surfaces in a Site of Ammonium Nitrate-Fuel Oil (ANFO) Blast. Malaysian J Forensic Sci. 2012;3(1):26-35.
[10] Allis DG, Korter TM. Theoretical analysis of the terahertz spectrum of the high explosive PETN. ChemPhysChem. 2006;7(11):2398-408.
[11] Allis DG, Zeitler JA, Taday PF, Korter TM. Theoretical analysis of the solid-state terahertz spectrum of the high explosive RDX. Chemical Physics Letters. 2008;463(1-3):84-9.
[12] Ivy MA, Gallagher LT, Ellington AD, Anslyn EV. Exploration of plasticizer and plastic explosive detection and differentiation with serum albumin cross-reactive arrays. Chemical Science. 2012;3(6):1773-9.
[13] 3-34.214 F. FM 3-34.214 Explosives and Demolitions. In: Army Do, editor. USJuly 2007.
[14] Remennikov A, Mentus I, Uy B. Explosive breaching of walls with contact charges: theory and applications. International Journal of Protective Structures. 2015;6(4):629-47.
[15] Wharton R, Formby S, Merrifield R. Airblast TNT equivalence for a range of commercial blasting explosives. Journal of hazardous materials. 2000;79(1-2):31-9.
[16] Kim H-S, Lee S-H, Moon H-Y. Strength properties and durability aspects of high strength concrete using Korean metakaolin. Construction and Building Materials. 2007;21(6):1229-37.
[17] Yi N-H, Kim J-HJ, Han T-S, Cho Y-G, Lee JH. Blast-resistant characteristics of ultra-high strength concrete and reactive powder concrete. Construction and Building Materials. 2012;28(1):694-707.
[18] Brandt AM. Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering. Composite structures. 2008;86(1-3):3-9.
[19] Weickert CA. Demolitions. Explosive Effects and Applications: Springer; 1998. p. 381-423.
[20] Lu X, Xie L, Guan H, Huang Y, Lu X. A shear wall element for nonlinear seismic analysis of super-tall buildings using OpenSees. Finite Elements in Analysis and Design. 2015;98:14-25.
[21] Savytskyi M, Nikiforova T, Grosman S. Rationale design measures to ensure the reliadility of high-rise buildings in progressive collapse. Збірник наукових праць [Полтавського національного технічного університету ім Ю Кондратюка] Сер: Галузеве машинобудування, будівництво. 2015(1):122-36.
[22] Renew W, Burgess M. Overview of environmental noise policies in Australia. Acoustics Australia. 2003;31(1):5.
[23] Li T-c, Liu J-z, Zhang H-d, Gao X. Integrated Technology of Dust Prevention in Explosive Demolition of Urban Buildings [J]. Blasting. 2012;4:030.
[24] Musser DW, Truitt RE, Braga J, Burns M, Courtois PD, Deardorff ME, et al., editors. Tilt-Up Concrete Structures1992: American Concrete Institute.