The colour of concrete can change as a result of heating. In some cases at above 300 degrees C a pink discoloration can occur. This normally coincides with significant strength loss and is due to the presence of ferrous salts in the aggregate or sand. This colour change tends to be more prominent in concrete with siliceous aggregates.

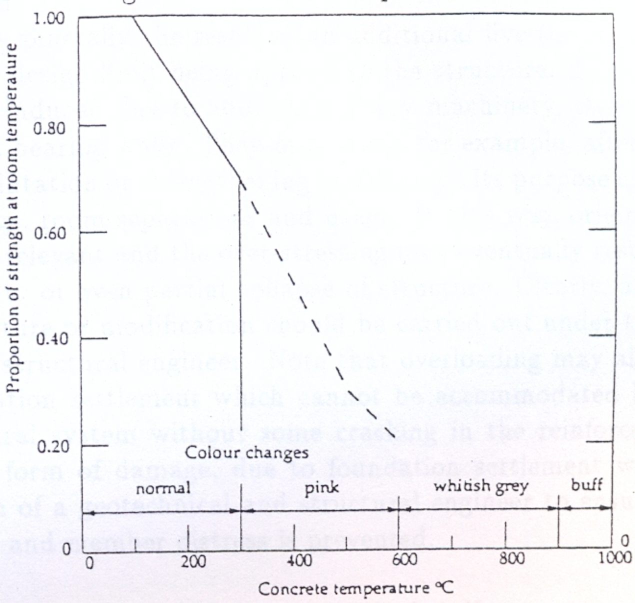

Figure 2.4. Influence of heat on compressive strength and colour.

Damage arising from the effects of high temperatures normally occurs in the form of spalling. and can generally be divided into two categories[17]

- explosive spalling, and
- sloughing off.

Explosive spalling appears only to occur for concretes of a particular range of moisture contents. It generally occurs within the first 30 minutes of exposure to heat and normally is characterised by a series of disruptions when surface layers of concrete are removed. Sloughing off tends to occur in beams and columns, over longer periods and is generally non-violent by nature. With this type of damage cracks form parallel to member edges and a section of concrete becomes detached to the depth of some plane of weakness such as a layer of reinforcement. This type of damage is often influenced by the type and properties of aggregate present.

2.1.8 Over-stressing due to quasi-static over-loading.

When the stresses in a structure are larger than the calculated design stresses due to particular type of loading the result will be over-stressing due to over-loading. Since in most cases there is a certain margin of additional safety (due

[17] Malhotra, H.L., *Spalling of concrete in fires*, CIRIA Technical Report No. 118, London, 1984, 36pp.

to the probabilistic nature of safety factors, characteristic loads and strengths) over-stressing does not automatically infer failure of the structure. However, unless a significant over-design of the member was made, at least one of the limit states will be reached.

Quasi-static overloading is generally the result of an additional live (or super-imposed) load beyond the design limit being applied to the structure. Typical examples include damage induced due to additional heavy machinery, storage loads and newly built load bearing walls. They may occur, for example, after a structure undergoes rehabilitation or strengthening and changes its purpose and consequently its furnishings, room separations and usage. In this way, original design loads are no longer relevant and the over-stressing may eventually result in total loss of serviceability or even partial collapse of structure. Clearly, any change of usage in a structure or modification should be carried out under the supervision of a qualified structural engineer. Note that overloading may also lead to differential foundation settlement which cannot be accommodated by the above ground structural system without some cracking in the reinforced concrete members. This form of damage, due to foundation settlement will require the joint attention of a geotechnical and structural engineer to ensure further ground movement and member distress is prevented.

2.1.9 Over-stressing due to dynamic or cyclic loading.

Here we review some basic damage patterns encountered due to dynamically or cyclically driven loading mechanisms. The emphasis will be placed on damage due to impact and blast loading on ordinary buildings which were not specially designed to provide protection against these effects.

Vibration.

Over-stressing due to vibration belongs to a group of time related mechanically driven deterioration mechanisms. Vibration is characterised by a periodic motion whereby the structure repeatedly passes through its equilibrium position. All structures are characterised by their fundamental (natural) modes of vibration. If the frequency of the imposed load closely matches a natural frequency of the structure, then it will exhibit resonance and in that condition even a small force amplitudes can cause it to collapse. Most vibration analyses are concerned with the serviceability limit states of the structure and the task is to ensure that the vibrations induced by forces of whatever source, remain inside allowable limits. Only extreme vibration cases lead to collapse of the structure. Examples would be failures of temporary stands in a sports stadium due to spectators jumping and the catastrophic failure of Tacoma Narrows bridge due to induced wind vibrations.

From the point of view of a repair engineer, the prime task would be to avoid alterations in the structure which would cause the change of the natural frequency of the structure resulting in a shift the response close to a resonant state. Any damage that is caused by excessive vibration should be remedied not only by repairing the physical damage to the structure but also by changing the modes of vibrations, either of the structure itself or of the external source of vibration which induced the damage.

Fatigue.

Over-stressing due to fatigue can sometimes be viewed as a special case of over-stressing due to vibrations (although the rate of cyclic loading might be such that inertial contributions are insignificant). It represents a progressive weakening of a structure or an element by repeated deformation. Fatigue as a source of failure may occur in industrial buildings where reciprocating machines induce vibrations which, after some (usually considerable) time, lead to fatigue of the material and reduction of its initial design strength or stiffness. In these situations repair engineers have to take care to chose repair materials that will have better fatigue characteristics than the original material. Offshore platform design requires careful fatigue loading checks, as these structures are subjected to repeated wave slamming over many hundreds of storm cycles.

Seismic excitation.

Over-stressing due to seismic excitation is a common source of failure for engineering structures in many parts of the world. The earthquake design regulations require that the characteristic dead loads used for static analysis should be used to determine the additional horizontal dynamic forces due to earthquake accelerations, known as *seismic forces*. An earthquake resistant structure should be designed to cope with a load combination of these seismic forces, dead loads and 50% of all imposed loads (see Eurocode 8, *Design provisions for Earthquake resistance of structures*). When repairs are carried on structures that were initially designed for earthquake loading, care has to be taken not to alter the structural system in a way which could make it more vulnerable to earthquakes. For example *shortening* a column by introducing rigid, load carrying walls may help for static loads but it will restrict its ability to move in a horizontal plane and so induce additional forces elsewhere that may cause severe damage to the structure exposed to an earthquake. So, a repair engineer has to remember that, from an earthquake analysis point of view, all constitutive elements of a building are structural elements although they may have been initially designed and built to carry no load. In other words, all additional walls, columns and other strengthening will contribute to the earthquake response of the structure as a whole and may potentially make it more vulnerable. Earthquake induced damage is a specialist area which has been extensively studied in the past 50 years. Interested readers should consult the voluminous Proceedings of the World Congress's on Earthquake Engineering.

Impact and blast.

Impact and impulsive loading are most extreme loading cases with a very low probability of occurrence during the lifetime of structures. They could be caused by for example military and terrorist activities but also in everyday situations (gas explosions, vehicle and other kind of collisions, heavy impacts, due to static load collapse of parts of a structure or debris loading). The main feature of these loads is that their duration is extremely short (measured in milliseconds) and that their peaks are usually considerably larger than for static design loads. The damage patterns in static and impulsive loading are different because of the different nature of the load. For example, in impulsive loading there is not enough time for static type crack growth, the strength of the material may increase furthermore, inertial and damping resistive forces are mobilized, which are not mobilized in static loading.

Definitions and terms.

- *Soft impact* happens when the deformation of an impactor (in comparison with the deformation of a resisting structure) is very large. In this case the kinetic energy of the striking body is completely transferred into deformation energy of the striking body, while the resisting structure remains undeformed.
- *Hard impact* occurs when the striking body is elastically rigid. In this case the kinetic energy of the striker is to a large extent absorbed by deformation of the struck body.

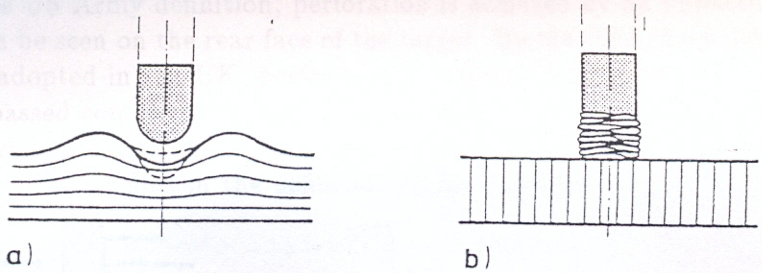

Figure 2.5. (a) Hard impact (b) Soft impact.

- *Close range explosion* occurs when the distance from the high-explosive charge to the target is equal or smaller than ten radii of the charge. They will produce a *point* load, that is, the structure will usually respond in local mode.
- *Far range explosions* happen when the distance from the charge to the target is greater than ten radii of the charge. They will usually produce

a more or less uniformly distributed load and the global response of the structure. The same mechanism will apply to all gas explosions.

- *Equivalent weight* is the weight of a spherical TNT charge which will produce the same blast effects as the explosive charge under consideration.
- *TNT equivalent* is a measure of the energy realised in the explosion of a given quantity of material which would realise the same amount of energy when exploded.
- *Total collapse* is the condition of a structural element in which it completely loses its ability to resist the applied blast load.
- *Partial failure* happens when one or more supports of a structural element collapse, resulting in a loss of strength and a reduction in the resistance.
- *Penetration* represents partial perforation where the target is not completely breached. Penetration depth is the depth of the crater developed in the target at the zone of impact.
- *Perforation* represents a complete penetration or hole from one side to another with and/or without an exit velocity. The term perforation implies that an impactor has passed through a target whereas penetration is defined as the distance the tip of an impactor has travelled into a target. This general definition is open to a number of interpretations. According to the US Army definition, perforation is achieved by an impactor when it can be seen on the rear face of the target. By the USA Navy definition, also adopted in the UK, perforation is achieved only when the impactor has passed completely through and emerged from the target. It is therefore crucial when stating damage levels (or interpreting a specification) to be unambiguous in the definition of the damage.

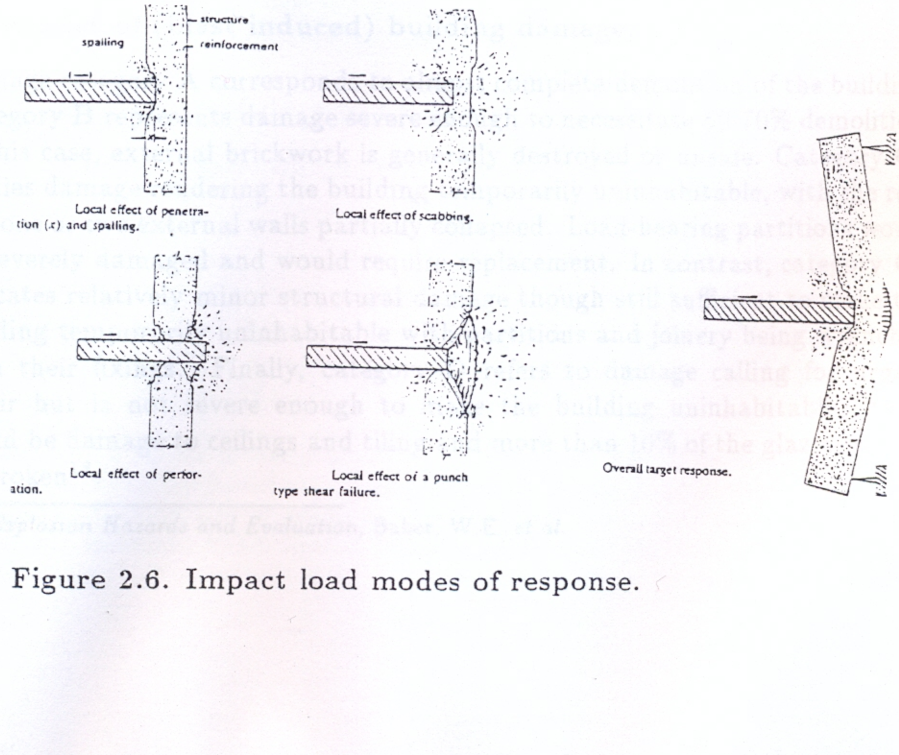

Figure 2.6. Impact load modes of response.

- *Reverse displacements* are one of the features of impulsive loading. The impulse, which usually can be determined, imparts kinetic energy to the structure, which deforms and acquires strain energy. The acquired strain energy is equivalent to the area beneath the resistance-deflection function for the structure. This function is the graph of the variation of the resistance that the structure offers to the applied loading as the displacement of the structure increases. This accumulated strain energy, when transferred into rebound, may be greater than the flexural resistance of the specimen in the other direction so reverse displacements occur. This is much more pronounced in steel since the rebound in concrete itself is usually small because concrete cracking causes internal damping. The presence of steel reinforcement in RC structures means that the rebound can be quite large, particularly for short duration loads on relatively flexible elements. Therefore structures must be designed to withstand significant reversals of loading. Elements which have large differences in reinforcements in upper and lower flanges are particularly vulnerable.

- *Scabbing* represents dynamic disengagement of the concrete of an element resulting from a tension failure in the concrete normal to its free surface (that is, the ejection of the target material from the opposite face of impact).

- *Spalling* is the ejection of the target material from the face at which impact occurred i.e., disengagement of the front surface of a structural component.

- *Crater formation* is the product of scabbing and spalling and as such may form on both sides of the target. For impact loading the inclination of the crater walls is the function of the impactor velocity.

Categories of (blast induced) building damage.

Damage category A corresponds to almost complete demolition of the building. Category B represents damage severe enough to necessitate 50-70% demolition. In this case, external brickwork is generally destroyed or unsafe. Category Cb implies damage rendering the building temporarily uninhabitable, with the roof and one or two external walls partially collapsed. Load-bearing partitions would be severely damaged and would require replacement. In contrast, category Ca indicates relatively minor structural damage though still sufficient to make the building temporarily uninhabitable with partitions and joinery being wrenched from their fixings. Finally, category D refers to damage calling for urgent repair but is not severe enough to make the building uninhabitable: there would be damage to ceilings and tiling and more than 10% of the glazing would be broken[18].

[18] *Explosion Hazards and Evaluation*, Baker, W.E. *et al.*