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Compound Growth or Compound Seismic Risk of Destruction? Some vulnerability lessons from the Izmit, Turkey, Earthquake of 17 August 1999

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ABSTRACT

The major earthquakes of 1999 have shown, again, that earthquakes are very good at discriminating bad buildings from good buildings. Bad buildings, which are those that unduly collapse or are severely damaged beyond repair, are picked out by an earthquake remorselessly over vast areas and from very large building inventories, with greater consistency and impartiality than any structural expert could manage. Earthquakes impact buildings as they have been constructed and without any preconceived or wishful ideas of what the buildings' performance should be like. An earthquake is the final arbiter of seismic resistive prowess in a region.

Bad buildings are highly vulnerable and their presence increases a region's seismic vulnerability. In a developed region, a big earthquake will inevitably affect many buildings, but it does not take a big earthquake to damage bad buildings. Consequently, a big earthquake will have a devastating impact in a region in which bad buildings are pandemic. This paper draws on field surveys carried out in the aftermath of the Izmit and Athens earthquakes of 1999 to show examples of regional vulnerability.

The high death toll caused by the Izmit earthquake was due largely to the collapse of many bad buildings. The paper shows that there is a lot of scope for reducing the building vulnerability in Turkey and that a modest reduction in vulnerability would reduce dramatically the number of casualties in future earthquakes. Using state-of-the-art computer models, the paper shows that an even greater reduction in vulnerability in Turkey towards the levels seen in California or Japan would not only reduce the property and economic losses substantially, but save many thousands of lives and the consequential social costs.

For this to happen, lessons not only have to be learnt, they have to be implemented. Mitigation measures for inducing an improvement in vulnerability may come in many forms, but they all require a culture in which the improvements can be made. Fostering a culture of heightened awareness to seismic risk, which includes the seismic hazard and the vulnerability of the building stock, can be difficult and very slow and very painful, if the only means of achieving this were through catastrophic seismic events, like the Izmit earthquake. The education of authorities, engineers, construction workers, home dwellers, businesses and insurers on the potential impact of earthquakes on buildings is a much more attractive alternative. An earthquake risk computer model is shown to be an ideal weapon in this educational process, pre-empting the need to suffer hard lessons from the next catastrophic earthquake.

Introduction

The best strategy for minimising the risk of catastrophic losses from earthquakes in regions of moderate to high seismic hazard is to have a building stock with a vulnerability which is improving with time. This requires either the retrofitting of existing buildings or that new buildings are designed and constructed to high standards, or both. Retrofitting a building can be expensive and time consuming: retrofitting the whole or large sections of an existing building stock would be a very daunting task. In contrast, the costs of implementing modern seismic resisting features in a new building can be marginal and yet these would provide enhanced safety for occupiers and reduce the property damage vulnerability. Importantly, this would reduce also the overall vulnerability of a building stock, as these new "good" buildings begin to take up a larger proportion of the whole.

This process of "good" building replenishment is essential, since very large proportions of building stocks in regions around the world consist today of buildings which were constructed prior to the introduction, in the last 20 years or so, of modern high seismic standards. In regions with low rates of construction growth the process of building replenishment would take a long time. But, relative to the return periods of major earthquakes in some parts of the world, even this slow investment would reap big benefits in the long run and should be encouraged. An interval between major earthquakes of 100 years and a compound annual growth rate of only 1%, for example, would reduce the old building stock to just 37% of the total (the proportion would be less than this, since not all the old buildings would survive). If all the compound growth were to consist of good buildings, this would mean that at least 63% of the building stock would show good earthquake performance.

In reality, some regions with high seismic hazard also have high rates of growth and in these cases this virtuous process would be not only more beneficial but absolutely crucial. This is because the converse situation of not replenishing the building stock with "good" buildings would have a similarly large, but in this case very detrimental, compound effect. A possible scenario would be a status quo, in which the construction process relies on ad hoc vernacular experience and over time assimilates very slowly some of the broader contemporary basic seismic engineering and construction expertise, as these develop. This, in effect, was the situation that prevailed almost everywhere up to the second half of the last century and is still the case in some regions. Relying on this method for improving the vulnerability of building stocks can, at best, be unreliable: the significance of basic engineering principles may not be understood, for example, and a regulatory framework may not emerge to guide, supervise or enforce proper practices.

At worst, new buildings could be constructed with a cocktail of poor design, poor construction and poor materials, giving rise to a building stock consisting predominantly of "bad" buildings. Bad buildings would collapse or would be severely damaged beyond repair, to an undue degree, during a major earthquake. The state and growth of these buildings would remain untested and unchecked until the next major earthquake, at which time it would be all too late.

Bad building practices are exacerbated by construction booms, during which the short term imperatives of housing needs or just simple profit are likely to override long term issues of building safety or structural performance in the next earthquake. In this environment, a compound annual growth rate of 2.5% would result in almost ***half*** the building stock being bad in just 25 years. Without a forcing environment which fosters constant improvement, the danger is that bad practices are introduced and perpetuated and, in a relatively short period, bad buildings become pandemic. The consequences of this scenario are impossible to eradicate in the short or medium term. In the meantime, the building stock and the population are at very high risk from the impact of major earthquakes and the consequences will be devastating when the next major earthquake does occur.

The paramount lesson here is not to wait for the next major earthquake to learn some more, but to make use of all the hard lessons that have been learnt already, from the many devastating earthquakes around the world, and implement these lessons.

Unfortunately, the situation surrounding the Izmit Earthquake of 17 August 1999 was one of these worst case scenarios. The ***new*** construction in the last 25 years accounted for an astonishing 67**%** of all buildings in the province of Izmit (Kocaeli), which includes the epicentral area around the Sea of Marmara, and this percentage was greater than the percentage for the country as a whole (which was 49%). Virtually all of these new buildings were "reinforced concrete" frame buildings and, because of the perceived technological jump from the vernacular adobe construction and the pervasive nature of the construction, the inhabitants appear to have assumed that these buildings had modern seismic resistance. After all, if all the buildings going up in a seismic region are of a particular kind, the lay person would be encouraged to think that this was for a very good reason: and to assume safety in numbers. In reality, due to the manner of design and of construction, the vulnerability of these buildings was exceptionally high and the seismic safety of the inhabitants was very low.

Reinforced Concrete (RC) and Building Vulnerability

The main reason for this may be found in the label "reinforced concrete", which literally can cover many defects. RC is a complex material which does not acquire basic structural properties just because it has been labelled as such. It consists of two components: concrete, which is good in compression, and embedded reinforced steel bars, which are good in tension. The two have to be combined properly in design and in construction for a building to exhibit proper engineering seismic resistance.

Unlike structural steel members, for example, the concrete in RC may be created in situ by mixing some simple ingredients: water, cement, sand, gravel. To get concrete of structural engineering quality to specified minimum standards of strength requires, however, a sophisticated knowledge of the material and rigorous production facilities and testing. Otherwise, the material that results may not be structural concrete with a specified minimum design strength but something that looks dangerously like it and has a strength of only a small fraction of the minimum. In Turkey, for example, the minimum design strength for concrete is around 16 MPa. This value is already low compared to other countries (USA 21 MPa), but in practice concrete strengths in Turkey are commonly even lower at around 10 MPa and in many cases are only around 6 MPa (Bayulke, 1998). This means that in these bad cases, the best that the concrete structural members can resist is only one third of the design loads, assuming that all the other design features have been constructed favourably: a considerable handicap indeed. In reality, there would be other defects (as described below) and the structural resistance would be even lower.

The steel bars in RC are also critical and these have to be placed in the correct quantities and configurations in order to make the RC design work. Every RC design may have a different quantity and configuration of steel bars, depending on the loads and geometry of the structural members. But once the concrete is poured, none of these critical steel bars is visible: a reinforced concrete column that was designed perfectly may have been constructed, in reality, without the necessary reinforcement and would look exactly the same as an adjacent column that did have the necessary reinforcement. It only takes one main structural member, such as a rogue ground floor column, to fail for a whole building to be compromised.

Although the ingredients of concrete are simple, they still have to be proper materials and mixed in the correct quantities and manner. Sea water will not do and neither will sea shells or beach sand as the aggregate. The salt in these materials would corrode the reinforcing bars, rendering them useless, and impair the "concrete". Surprisingly, these materials were found as constituents in many of the "RC" buildings around the Sea of Marmara, struck by the Izmit earthquake. Not surprisingly, many of these buildings collapsed (Figure 1).

Figure 1 (left) Sea shells in “concrete”

Figure 2 (right) Inadequate reinforcement in “RC” structural members
Both found in collapsed buildings after the Izmit earthquake

The steel reinforcing bars also have to satisfy minimum standards for them to perform properly. They should not be smooth or their surface pitted with corrosion prior to installation and they should be placed in the quantities and configurations demanded by a proper seismic design, both along and around structural members.

Missing bars or even too many bars (such that there is very little or no concrete to provide the bond between them) are just as bad. The bars also have to be of the correct length inside the concrete: splicing separate bars by using short overlaps or abutting the ends of bars together is structurally useless. Indeed, hooking the ends of reinforcing bars at column-beam joints (thereby creating hinges rather than moment resisting joints) in buildings devoid of any shear walls (meaning the joints are supposed to carry all the lateral loads from an earthquake), is tantamount to a death wish. Yet these defects in steel reinforcements were observed in many of the damaged and collapsed “RC” buildings after the Izmit earthquake (Figure 2).

The cement also has to be of good quality and mixed in the correct quantities with the aggregate and water in order to get concrete of a required minimum strength. Again, deficiencies were found in these aspects after the Izmit earthquake.

RC may be seen therefore as an ideal material for hiding defects in design, in materials and in construction and would be attractive to the ignorant or the unscrupulous. “RC” is very forgiving under normal static loads, to the extent that unskilled (or other) people only need to make it look like RC to support buildings that are 5, 6 or even 8 storeys high, the typical range of storeys in the hinterland of north-west Turkey struck by the Izmit earthquake. But pseudo RC buildings do not tolerate dynamic loads from a major earthquake at all: they can collapse and become death traps in seconds.

RC Design and Building Vulnerability

Another crucial aspect in the performance of RC buildings is the structural design that is chosen to resist vertical and horizontal loads. Previous earthquakes have shown that the inclusion of shear walls reduces the severity of damage and the incidents of collapse. Shear walls increase the structural redundancy of a building and absorb energy effectively, allowing some structural members to be distressed considerably, or even fail, without causing the complete collapse of the structure. This kind of fail-safe feature would be essential in the bad “RC” buildings described above, in which defects exist in the structural members themselves. But, incredibly, not a single shear wall was observed in AIR’s survey of the whole of the area around the Sea of Marmara affected severely by the Izmit earthquake, which included many thousands of buildings in an area from Istanbul and Yalova to Adapazari (Figures 3 and 4).

Without continuous structural shear walls, any discontinuities in the lateral stiffness of a building (such as the ground storey with the open columns in Figure 3, on which the upper three storeys sit as a stiff block) are likely to result in failure of the storey and collapse of the building. This type of collapse, termed “soft storey” collapse, is very common in major earthquakes (Figure 5). It should be noted that the external expanse of walls seen commonly on buildings (Figures 3 and 5, for example) are not structural shear walls, since they consist only of in-fill masonry (mostly hollow brick or hollow concrete blocks) and they are not tied to the “RC” frame (see Figures 4 and 6).

Figures 3 and 4 Buildings under construction alongside the Trans European Motorway between Istanbul and Izmit: cantilevered floor slabs and no shear walls

Another common feature in the "design" of these buildings in this region is to have floor slabs which cantilever off the perimeter structural columns, in order to augment the floor area above the ground floor (Figures 3 and 4). In many cases, for example, these cantilevers overhang pavements. The external walls of the buildings are built up from the edge of the cantilever at each floor, using brick masonry or, sometimes, concrete parapet or balcony features. These cantilevers therefore have to carry heavy loads. In many cases, the ratio (*r*) of the length of cantilever (*c*) to half the distance between the outer columns (*b*) is large. This geometry for the structural loads tends to reduce stability and the stability decreases as the ratio r increases (think of an inverted pendulum).

Figure 5 (left) Typical soft storey collapse

Figure 6 (right) Partial collapse of building due to failure of cantilevered floor slabs

In the case of narrow buildings the ratio r may be as high as 30% and the loads on the outer ground floor columns may be increased by as much as 50% compared to the loads for the case without cantilevers. This level of additional load, brought about solely by the configuration of a building, can make the difference between no collapse and collapse (Figure 6): between few or no casualties and many casualties.

Pandemic Bad Vulnerability

As we have seen, proper RC seismic design and construction demands specialised skills and should be treated with due respect and care. The alternative is the creation of a pandemic bad vulnerability and this cannot be viable for the long-term social and economic prosperity of a nation.

RC has been used as a modern panacea for solving housing needs in many seismically active regions. It allows buildings to be constructed taller and bigger than the traditional adobe housing, with all the modern conveniences. Reliance on one construction type can be dangerous, however, since this increases the risk of pandemic bad vulnerability. If bad practices are introduced, by, for example, vernacular builders who do not understand the engineering aspects let alone the seismic aspects, these can spread very quickly to all the new building stock. If a diversity of skills for different design and construction types is not mastered, the skills' base can stagnate and bad practices can grow.

The label "reinforced concrete" has been misused and has been applied to very large numbers of buildings that are nothing of the sort in engineering terms. In these circumstances of pandemic bad vulnerability, the risk of suffering large numbers of casualties and huge economic losses from a major earthquake is very high indeed, as demonstrated by the Izmit earthquake. *Whole* groups of buildings with these pandemic bad characteristics will be damaged severely or will collapse: if one building goes, all are likely to go in a similar manner (Figures 7 and 8).

Figure 7 (left) Structural failure (soft storey) of a group of similar buildings

Figure 8 (right) A whole street suffers "RC" failure and soft storey collapse

It is hard to comprehend the scale of the effect of pandemic bad vulnerability without first hand experience. But, imagine every multi-storey "RC" building as a potential death trap without quite knowing which will or will not collapse and this comes close to the situation surrounding the Izmit event (Figures 9 and 10). This earthquake did a thorough job of picking out bad buildings: it destroyed around 66,000 housing units and damaged "moderately" another 66,000 (which are deemed to be dangerous to live in without repair and *strengthening* measures) and damaged "slightly" another 80,000 (which still require immediate repair). At least 17,000 people were killed and 44,000 were injured. At least 250,000 people were made homeless. The need for better buildings is clear.

Figure 9 (left) Various levels of damage: from complete disintegration (rubble in foreground) to soft storey failures to collapse of external masonry walls

Figure 10 (right) Typical death trap caused by complete disintegration of vertical supports and collapse of all floors. Notice that an adjacent building remained standing and was therefore not a death trap, even though it may have suffered damage in the RC structural members

Bad buildings are not confined to Turkey. In the Athens earthquake (M5.9) of 7 September 1999, many of the building collapses and much of the severe damage could be attributed to bad structural features. In one case, for example, a water drainage pipe was found to have been inserted inside a “RC” corner column of a two storey building: the column collapsed and the building was torn apart. This demonstrates that even moderate magnitude earthquakes will pick out and destroy bad buildings. But a moderate magnitude earthquake will affect a much smaller area than a large magnitude earthquake like the Izmit earthquake (M_w7.4), and this is a big difference in terms of the impact that pandemic bad buildings will have. Another big difference is that the duration of ground shaking will tend to be shorter in a moderate earthquake than in a large earthquake and, consequently, some bad buildings may be saved from potential imminent collapse just by not getting a few extra cycles of loading. It is the presence of bad buildings at pandemic levels, rather than the occasional occurrence, that will lead to widespread devastation in a region that is affected by big earthquakes.

None of the lessons highlighted above were new. The consequences of each of the defects and, importantly, the cocktails of defects were known from previous earthquakes and from basic engineering principles. Moreover, all of the lessons have been highlighted and experienced in recent earthquakes in Turkey itself: in 1966 (Varto, M6.8), 1967 (Mudurnu, M7.1), 1992 (Erzincan, M6.8), 1995 (Dinar, M6.1) and 1998 (Adana, M6.2), for example.

In 1966, in the aftermath of the Varto earthquake, Ambraseys and Zatopek (1968) observed *"Reinforced concrete structures … failed completely due to improper construction and poor building materials, while nearby houses of local construction suffered only some damage. This illuminates the need for better methods of construction and the use of better materials rather than for advancements in design, particularly in developing countries. The behaviour of these structures points to the need for supervision during construction and for training of the local builder in the proper use of building materials rather than for more advanced codes and regulations."*. These lessons were fomulated before the introduction of the modern earthquake resistant design code in Turkey in 1975 and before the construction boom of the 1980s and 1990s, but they do not appear to have been implemented. As always, an earthquake will impact a building as constructed and not as intended on the drawing board or in building codes.

In 1967, the city of Adapazari was virtually destroyed by the Mudurnu Valley earthquake. Uzsoy and Ersoy (1969) reported that *"The observed damage shows that elaborate calculations for the design of structures to withstand earthquake forces are of little use unless they are based upon sound concepts, proper details, and are carried out by construction practice of good quality."*. In August 1999, the reconstructed Adapazari was again virtually totally destroyed by the Izmit earthquake, even though the reconstruction had taken place in “modern” times and with the benefit of the 1967 experience.

Similarly, in 1992 the city of Erzincan was damaged severely even though it had been rebuilt (and even relocated just to the north) after the devastating great Erzincan earthquake (M7.9) of 1939 (Earthquake Spectra, 1993).

The Chief of the Earthquake Engineering Division, Ministry of Public Works and Settlement, Turkey, reported after the Adana earthquake that “*The damage of the reinforced concrete buildings in this Earthquake once again proved the low quality of the reinforced concrete buildings in Turkey …*” (Bayulke, 1998).

Potential Impacts of Improving Vulnerability

It is possible to design and construct buildings that will resist major earthquakes, such that the main causes of casualties (the incidents of total or partial collapses) and damage are reduced. This was demonstrated in the Izmit event by the many cases of buildings that remained standing next to buildings that had been reduced to rubble. Had all the buildings been like the former, the levels of damage and casualties would have been much smaller.

The potential benefits of improving the vulnerability of a building stock may be quantified, using historical data of damage and casualties and the levels of improvement that are possible. The data from the Izmit event show that there is a strong correlation of increasing casualties (killed and injured) with increasing number of buildings damaged (Figure 11). As shown, this correlation is consistent with that from thirteen other major earthquakes in Turkey, which occurred from 1914 to 1998. This indicates clearly that the safety of buildings had not changed materially in a whole century, even though the methods of construction had shifted from vernacular adobe to "reinforced concrete". The data on deaths and collapsed buildings are likely to be more objective than those on injured people and damaged buildings and they have been given greater weight in comparisons with data from different events.

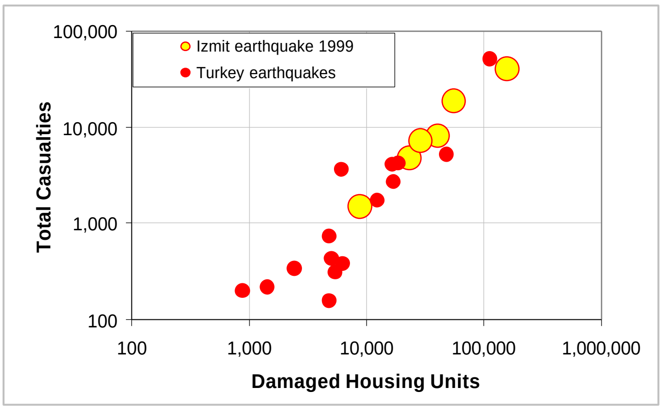

Figure 11 Increase in total casualties with total damaged housing units, from the Izmit event (aggregated by province and total) and from 13 other earthquakes in Turkey from 1914 to 1998

By reducing the number of buildings damaged, the number of casualties could be reduced. The scale by which this could happen may be assessed from the recent experiences in California, where less than 80 people were killed by either the Loma Prieta (M7.1) or the Northridge (M6.7) earthquakes, or in Taiwan, where around 2400 people were killed by the great Chi-Chi (M7.6) earthquake in 1999.

The vulnerability of RC buildings in California or Japan may be viewed as benchmarks, to which it would be possible to reduce the vulnerability of ***new*** RC buildings in Turkey. The data suggest that the number of deaths and of total casualties in Turkey would be reduced by around 35% to 75% and by 20% to 50% respectively by increasing the proportion of good buildings to around 20% to 50%, through a process of good building replenishment (Figure 12). Had this good building replenishment process taken place in the last 25 years in the areas affected by the Izmit event (during which period the proportion of new buildings in the province of Izmit was 67%), up to around 14,000 lives would have been saved. Achieving in Turkey the standards of RC buildings in California or Japan would save over 95% of potential deaths.

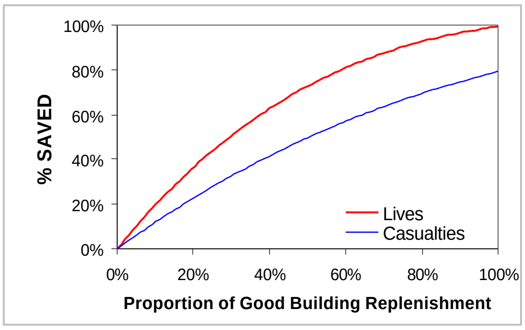

Figure 12 Potential increase in lives and casualties that would be saved as the proportion of good buildings in the building stock increases

Improvements in building stock vulnerability, through good building replenishment, would result also in substantial reductions in property losses. This effect may be quantified easily by using a computer model of earthquake risk analysis, such as the AIR earthquake risk model. This model combines the earthquake hazard, the vulnerability of buildings and the types and location of buildings in the region of interest to analyse the potential physical damages and insurance losses from earthquakes and the probability of these damages and losses occurring.

The computer model allows a very large number of earthquakes to be run in order to derive a complete curve of potential losses and associated probabilities. In addition, the computer model allows an earthquake such as the Izmit event to be reconstructed and hypothetical scenarios to be run with varying levels of vulnerability and mixes of building types in order to assess the effects of good building replenishment and the consequential improvements in vulnerability.

It has been a common phenomenon around the world for the awareness of the local risk to a natural hazard to erode after a generation or so, without the occurrence of any damaging events. The pace of change (population expansion, economic development) is so great nowadays that this erosion of risk awareness may occur even more rapidly. Large changes in building construction types, building stock and population concentrations, values and geographical distributions can take place before the occurrence of the next catastrophic event, the very event that would cause shifts in awareness and attitudes to risk. In this scenario, similar to that surrounding the Izmit event, the assets at risk may be increasing whilst the risk awareness and the risk-mitigating measures decrease. In these circumstances, the results of the computer model may be used very effectively, on an on-going basis, to educate and inform decision makers and all those responsible for building construction and policy and to assist in the formulation of optimum cost-effective improvement strategies. The computer model would act as a constant reminder of the potential devastation that the next major earthquake would cause if no improvements were made. These processes would be made possible without needing to have a damaging earthquake to act as a catalyst for change.

Conclusions and Recommendations

The manner in which buildings are designed and constructed in Turkey has to be improved. For this to happen as a matter of course, a quantum change needs to take place in the culture surrounding building construction. A start has to be made at some time if the long term benefits of good building replenishment are ever to be achieved and pandemic bad vulnerability reduced. Now, in the immediate aftermath of the catastrophic Izmit earthquake, would be an opportune time to focus on the problems and resolve to create a culture in which buildings may be constructed better consistently. To this end, the following recommendations are made.

Two basic engineering improvements would go a very long way towards achieving better building seismic performance. Firstly, there is huge scope in Turkey for improving the quality of concrete – and this should be done. Increasing the *minimum* concrete strength to at least 21 MPa for all new buildings would increase their strength by factors of 3 or 4 in many cases. In order to ensure that at least the minimum strength is achieved, the concrete strength should be tested and approved by a designated independent authority during the whole construction process, before the final concrete is poured. The testing and approval should include all the materials used in mixing the concrete. Secondly, there is also huge scope in Turkey for improving the quality of building design by using structural shear walls. These should be made mandatory through a designated design and construction approval system.

Other critical areas for improvements are in technical education and in the regulatory environment. Improvements here would be essential in order to change the culture towards one of good building replenishment. A procedure (preferably mandatory) of continuous education and training in proper reinforced concrete design and construction should be set up for all those involved in the construction of a building, including builders, engineers, architects and regulatory authorities, both existing and those in the future. At the same time, a mandatory system of independent approval, supervision and inspection should be set up for designated phases of the design and construction process, including before, during and at completion of a building. In order to ensure the safety of buildings, a mandatory system of Certificates of Building Safety should be set up, whereby a Certificate would have to be obtained from a designated authority before any occupation of a building may take place.

Insurance is another regime by which improvements in building vulnerability may be forced and encouraged. Each building, for example, should have mandatory insurance in place before the building may be occupied. This would create another tier of checks independent of government authorities and would be a catalyst for the insurance industry (both domestic and international) to demand better buildings, with proper engineering design and construction methods, and to foster an environment in which this may be achieved.

The lessons experienced in the Izmit event must be digested and implemented for the vulnerability of the building stock in Turkey to improve and for casualties and losses to be reduced in future earthquakes. A start has to be made in instilling a culture of good building design and construction, in order for new buildings to be "good" buildings and the overall vulnerability of the building stock to improve with time. This is of paramount importance.

The education and training of all those responsible for building construction would be facilitated and enhanced by the use of state-of-the-art computer models, such as the AIR models. These models are able to assess the impact on potential earthquake losses of mitigation measures, improvements in vulnerability and even the location of buildings, before the buildings are built and before any damaging earthquakes occur.

The vast reconstruction that will be necessary in the area devastated by the Izmit earthquake should take place only with the benefit of measures such as these in place.

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