Latent Building Defects: Causes and Design Strategies to Prevent Them

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Abstract: Building designers' decisions affect long term quality and life cycle cost of buildings. Designers' decisions are usually latent in nature and hard to detect at the early stage of construction. This research looks at failure mechanisms that caused design-related latent defects and the design parameters that could prevent these defects. A 9-month building survey on 74 buildings found that the three most important design-related failure causes were weather impact, impacts from occupants, and loads and moisture from the wet areas. Insufficient considerations for these failures causes were found to be the key in preventing these defects. The design strategies that could successfully prevent triggering these defects include aligning material performance against adverse weather conditions, preventing impacts from occupants and loads, preventing water leakage, improving specifications and improving design clarity, details, and layout. There are huge amount of standards and codes available internationally, however, each is designed specifically to overcome regional problems. This research confirms the need for designers to (1) consolidate regional standards and codes; (2) develop in-house database using existing standards and codes, and lesson-learned from defects gathered by property managers; and (3) to apply this knowledge to eliminate latent defects from future design. This research also confirms that such knowledge can be developed using existing records of property managers.

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Introduction and Background

Eliminating latent building defects is a difficult task. Most latent defects appear only during the occupancy stage and getting access into occupied buildings to acquire information on these defects can be difficult. Design deficiencies are major contributors to latent defects and such deficiencies can only be prevented by improving design (Low and Chong, 2004).

With many other issues, like thermal insulation, energy consumption, and financial constraints, designers are unable to dedicate adequate effort to eliminate latent defects from their designs. Many of these defects continued to be repeated in many buildings and enormous finances had been committed for defect rectification.

It is difficult to detect latent defects due to the time frame that these defects appear. Unless such defects are serious enough to cause occupants to complain to the authorities or file law suits, most of these defects rarely surfaced to the public. Many of these less significant latent defects were related to architectural finishes but this research also found several structural and geotechnical defects. This paper focuses on identifying design strategies and failure causes so that latent defects can be prevented at the design stage.

Design Parameters and Causes of Latent Defects

Assaf et al. (1996) survey on 11 major groups of defects through literature and interviews showed that defects were generated from civil design, architectural design, design issues on maintenance practicality and adequacy, defects due to consultant firm administration and staff, defects due to construction drawings, defects due to contractor administration, defects due to construction materials, defects due to construction equipment, and defects due to specifications.

Contractual concepts, such as specifications, are used to determine the causes and responsibilities of defects especially in the grey areas, though contracts rarely specify the responsibilities of defective specifications. Contractors and designers are jointly responsible for defects that are derived from poor specifications. Poor specifications are generally the fault of designers but failure to comply with specifications is the responsibility of contractors. There are implied warranties on design and construction works that protects building owners from possible failures (Thomas et al., 1995). Determining responsibilities through legal concept can be a hassle since no contractual document is readily available at the time when defects occurred. However, it is rather clear that defective specifications are usually associated with the designers.

Low and Chong (2004) had shown that design is the most important driver of latent defects in building as the condition survey showed that design could have prevented at least 66% of

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all latent defects found during the early stage of occupancy.

Atkinson (2003) found that managerial errors accounted for more than 82% of all errors committed and that managerial errors have hidden or latent characteristics, suggesting that these errors are not visible at the construction stage and both clients and designers might have huge impact on such defects.

Anderson's (1999) analysis showed that the distress on the spalling brickwall that caused vapor infiltration was due to deficiencies in workmanship, material, and design. An adjustment to the interior environment, i.e., the ventilation system, was recommended to control humidity and air flow which in turn reduce the effect on vapor infiltration.

Watt (1999) seemed to suggest that inappropriate materials applied to the building and poor expert decision making caused building defects. Anand et al. (2003) suggested that better design could correct some workmanship generated defects in masonry works.

BRE (1991) and Richardson's (1991) research on defects had stressed the importance of weather, environmental conditions, soil impact, poor design, chemical attack, structural movement (due to poor structural design), installation method, workmanship, maintenance issues, and site working conditions. These suggested that defects could have been prevented if considerations were made on the conditions building elements were subjected to.

The garden roof alternative design proposal in Wong et al. (2002) can help reduce the amount of roof defects by reducing the possibility of roof leakage and increase the life of the roof, highlighting designers' ability to contribute to defect reductions with their designs. It also suggested that designers' ability to design against the environment would help eliminate many latent defects.

Calder (1997) found that poorly worded specifications and unclear designs often lead to lower construction quality. The Seeley (1987) study also showed that 58% of defects were caused by faulty design, 35% from operation and installation, 12% from poor materials and systems, and 11% from unexpected user's requirements, while a survey conducted by Ransom (1981) showed that fair wear and tear accounted for 56% of all the defects found while 20% were accounted for by poor design decision, and 20% from materials and workmanship.

Josephson and Hammarlund (1999) exhibited the chain effects of building defects, highlighting the importance of process control, management, knowledge, and the integration of existing knowledge to stop the chain reactions that would result in building defects. Andi and Minato (2003) also identified that inadequate information, unawareness, wrong assumptions, and lack of knowledge, alongside other organizational and motivational factors, contributed to defects at the design stage.

Andi and Minato (2003) identified inadequate information, unawareness, wrong assumptions, and lack of knowledge, alongside other organizational and motivational factors, as contributory factors to defects at the design stage. Ilozor et al. (2004) showed that some defects caused several other defects, and preventing those defects could eliminate many other defects.

Design decisions are important drivers of building quality. However, designers lack necessary knowledge and information that could help prevent latent defects in their designs. There is a lack of a centralized defect database where designers could find solutions or determine problematic areas before finalizing their designs. Architects rarely refer to standards and codes developed by engineers. As a result, similar defects are often repeated. Designers are unable to appreciate the seriousness of environmental impacts on their designs and the multifaceted nature of defect responsibilities deviate attention from design improvement. Thus, developing a knowledge database using existing knowledge and educating designers are the two keys in preventing defective designs that lead to latent defects. Most importantly, designers need to know what to focus on in order to prevent the most serious latent defects.

Research Objectives and Methodologies

The objective of this research is to identify the most important design strategies and failure causes that could help prevent latent defects from poor design decision. Latent defects from the most reliable sources were first collected and evaluated. Defects that were caused by design were then grouped together for further analysis.

Since most building defects become visible 2 years after occupancy and prevailing Singapore law requires buildings to be repainted once every 5–6 years and defects were usually rectified during repainting, defects data were collected from buildings between 2 and 6 years old. Defects were only collected from commonly constructed buildings in Singapore to ensure that the data are representative of the defects commonly found in the country.

Data Collection Methodology

Designers based their design decisions on what they know and most designers do not have access to the long term performance of their design. In Singapore, building performances and maintenance are usually left to the property managers and they rarely communicate with the designers. As a result, poor design decisions continue to be repeated in every new building. Industry has even tolerated some of these defects. On the other hand, designers rarely seek advice from the property managers about possible problems in their designs. Although many designers will convey such issues to the owners, the owners rarely pass on such information to the maintenance agents. Many owners even assumed that property managers are knowledgeable enough to know what may happen. Many defects were latent and occurred a few years after occupancy, when it is too late to verify.

The best sources of latent defects come from those who have regularly come into contact with these defects, like the maintenance contractors and property managers. However, proper records are also important to ensure data accuracy and data collection efficiency.

Data were collected from the records that were kept by the property managers maintaining the buildings. Interviews and guided walks around buildings were also conducted to verify the data that they had provided. These data were screened thoroughly and standardized according to the methods adopted by the public agency overlooking building quality in Singapore.

To further eliminate variability and improve data quality, buildings that fail one of the following criteria were not selected: (1) no proper property management setup; (2) no proper defects records; and (3) property manager or managing agent maintaining the buildings for less than 1.5 years. One hundred eighty buildings were initially selected and surveyed but only data from 74 buildings were used for this research as many did not pass the qualifications. A total of 35 institutional buildings, four hospitals, 13 residential, 11 commercial, and 11 others types of buildings were selected.

Table 1. Latent Defects Major Failure Causes due to Poor Design Decisions

	Weather Impact (%)	Moisture from the wet areas (%)	Impacts from occupants and loads (%)	Vandalism or accidents (%)	Deteriorates faster than expected (%)	Percentage due to poor design (%)	Total number by poor design (%)
Roof	7.73	3.20	2.43	0.00	2.88	82.03	335
M&E	0.00	1.83	5.67	3.97	5.04	73.12	1,249
Ceiling	6.19	32.42	3.24	35.76	3.60	73.10	1,021
P&S	1.03	12.79	8.91	11.92	11.51	72.09	809
Door	2.58	0.00	12.96	10.60	28.06	61.27	969
External Wall	40.72	12.33	4.86	7.28	3.60	59.44	1,077
Windows	3.09	0.46	10.93	15.89	1.44	59.79	1,337
Int. Wall	9.79	27.85	24.70	4.64	13.67	53.12	2,064
Floor	5.15	6.39	10.53	1.32	12.23	39.34	1,762
External Works	22.16	2.28	7.29	6.62	14.39	15.22	348
Total	52.76	9.87	24.33	5.48	6.39	58.67	1,0971
			Distribution of defects among all the causes				

Information Grouping, Categorization, and Strategies Identification

Literature reviews and expert opinions were used to develop five defects categories and defects were classified under these categories. These categories include location, materials, defect description, failure mechanisms, elements, design parameters, and roots. These categories are further divided into subgroups. Defects were categorized into the subgroups that best described those defects. These subgroups include:

1. Elements: The 11 elements are: floor, external wall, internal wall, doors, windows, mechanical and electrical systems (M&E), plumbing and sanitary system (P&S), roof, ceiling, and external works.
2. Materials: Materials of the defective elements.
3. Defect descriptions: The defect descriptions were adopted from the public agency. The defect inputs from the property managers were verified and standardized by the building surveyors from the research team who ensured that all descriptions were similar to those used by the public agency. The team made sure that all the defects were properly described and no defect was repeated twice under different headings.
4. Roots of defects: Roots of defects generally define the defect origins. The origins can be traced to main participants responsible for the defects: designers, contractors, material suppliers, and maintenance contractors. These roots are "design (D)," "workmanship (W)," "materials (M)" and "maintenance (Mt)." The definitions of these five root failure mechanisms of defects are as follows:
   - Design: defect(s) caused by poor decision(s) in design. Designers' decisions include specifications of materials, layout, and integration between different materials and systems.
   - Workmanship: defect(s) caused by poor installation methods, including poor mixing of materials, poor handling of materials (that lead to defects), poor planning (from the contractor) that lead to poor completed quality, failure to provide proper joints, gaps or materials to avoid defects, etc.
   - Materials: defect(s) caused by poor material quality. Materials are only expected to perform up to their required standards; however, if they are exposed to higher impact, they will not be considered poor in terms of quality. When this happens, the root cause can be directed toward design or workmanship.
   - Maintenance: defect(s) caused either by materials or systems that are not maintained properly or maintenance that is irregular or nonexistent at the occupancy stage.
5. Failure mechanisms of defect: literature reviews and expert opinions suggested that there could be 15 failure mechanisms of defects and these were used in the survey. However, during the course of data collection, property managers identified that only 12 were significant. Of these 12 failure mechanisms, five were significantly contributed by design decisions.
6. Design strategies: seven design strategies were initially identified but five were found to be signification. These parameters include:
   - Aligning material performance against adverse weather conditions;
   - Preventing impacts from occupants and loads;
   - Preventing water leakage that cause other defects;
   - Improve specifications; and
   - Improve design clarity, design details, and layout.

Since any defect can have more than one root and cause, the number of recorded failure mechanisms and root surpassed the total number of defects found. Defects collected for this research only included those that were serious enough to require repair or make it to the property managers' records.

Data Analysis (Part 1): Failure Mechanisms of Latent Defects due to Poor Design

More than 18,704 defects were found and nearly 60% (10,971) of these defects were preventable with better design, 33% with better workmanship, 24% with better materials, and 4% with better maintenance. This analysis showed that design is an important function in eliminating latent defects. This research focused on defects caused by poor design decisions.

The five key design-related failure causes of latent defect are shown in Table 1. The table provides a clear picture of how poor designs caused latent defects in different building elements. 52.76% of the design-related defects were due to inappropriate consideration for the weathering elements. Of these 52.76%, 40.72% were external wall defects, 22.16% were external works

Table 2. Design Strategies Against Latent Defects

	Improve materials (%)	Protection against impacts (%)	Prevent water leakages (%)	Improve specifications (%)	Design, layout, and details (%)
Int. wall	23.71	24.70	27.85	13.33	3.50
Ext. wall	14.15	4.86	12.33	6.06	2.80
Ceiling	11.72	3.24	32.42	3.64	4.20
Door	9.00	12.96	0.00	16.36	19.58
P&S	10.50	8.91	12.79	12.12	12.59
Floor	9.75	10.53	6.39	6.67	9.09
Ext. works	6.84	7.29	2.28	7.88	15.38
Windows	4.50	10.93	0.46	7.88	6.99
M&E	2.53	5.67	1.83	18.18	13.99
Root	3.56	2.43	3.20	3.03	8.39
Total number of defects	53.08	14.36	11.07	7.59	6.58

defects, 9.79% were internal wall defects, 7.73% were roof defects, 6.19% were ceiling defects, and 5.15% were floor defects. 24.33% of the design related defects were due to occupants and loads related to wear and tear and impacts from the occupants and their loads. Of these 24.33%, 24.70% were internal wall defects, 12.96% doors defects, 10.93% windows defects, 10.53% floor defects, 8.91% plumbing and sanitary defects, 7.29% external wall defects, and 5.67% mechanical and electrical systems defects. 9.87% of the design-related defects were due to moisture from the wet areas. Of these 9.87%, 32.42% came from ceiling, 27.85% from internal wall, 12.79% from plumbing and sanitary, 12.33% from external wall, 6.39% from floor, and 3.29% from roof.

6.39% of the elements were found to have deteriorated faster than usual and no apparent reasons can explain the phenomenon except that designers have underspecified the designs. Of these 6.39%, 28.06% came from doors, 14.39% came from external works, 13.67% from internal walls, 12.23% from floors, 11.51% from plumbing and sanitary, and 5.04% from mechanical and electrical systems. Finally, vandalism and accidents from the occupants caused 5.48% of all design-related defects. 35.76% of all vandalism and accidents were done to ceiling, 15.89% to windows 11.92% to plumbing and sanitary, 10.6% to doors, 7.28% to external walls, and 6.62% to external works.

Data Analysis (Part 2): Design Parameters to Prevent Latent Defects

Table 2 lists the prevention methods or design strategies that could be used to eliminate building latent defects. 53.08% of the design-related latent defects could be prevented by using more appropriate materials. Of these 53.08%, 23.71% were due to internal walls materials, 14.15% external walls materials, 11.72% ceiling materials, 10.5% plumbing and sanitary, 9.75% floor materials, 9% door materials, and 6.84% external works materials. The materials in these elements could have been changed to prevent latent defects.

14.36% of the design-related defects were caused by protection deficiencies against vandalism, accidents and wear and tears of the building elements. Of these 14.36%, 24.7% were deficiencies on internal walls, 12.96% doors, 10.53% floors, 10.93% windows, 8.91% plumbing and sanitary, 7.29% external works, and 5.67% mechanical and electrical systems.

11.07% of the latent defects could have been prevented if there were no water leakage. Of these 11.07%, 27.85% were from internal walls, 32.42% ceilings, 12.79% plumbing and sanitary, 12.33% external walls, and 6.39% floors. 7.59% of these latent defects could be eliminated with better specifications or clearer designs. Most unclear designs and improper specifications came from doors (16.36%), mechanical and electrical systems (18.18%), internal wall (13.33%), external works (7.88%), windows (7.88%), floors (6.67%), and external walls (6.06%).

6.58% of the design related defects could be eliminated with better design and layout. Designers committed most errors on layout and designs of doors (19.58%), external works (15.38%), mechanical and electrical systems (13.99%), plumbing and sanitary systems (12.59%), floors (9.09%), roofs (8.39%) and windows (6.99%).

Detailed Analysis

Brief Discussions on Internal Wall Defects

There were 1,084 cases of plaster cracks and 748 cases were associated with poor design. Many of the plaster cracks were found in wet areas and exposed to high temperature. Continuous wetting and drying of concrete walls in the wet areas encouraged contraction and expansion. Movements from contraction and expansion cracked plaster. Poor waterproofing caused moisture to travel from the floor onto the wall and plaster also cracked as a result. Moisture trapped inside the concrete forced cracks to form on the surface when moisture tried to find a way out. The moist environment further encouraged the painted wall surface to expand and contract, thus, leading to cracks. Poor workmanship (especially when plastering materials were not mixed properly before installation) and lack of expansion joints further worsen the cracks. Plasters cracked from the continuous wetting and drying alongside the extreme heat from the external environment. There are many solutions to these problems, like avoid using plaster on walls that had frequent contact with moisture and heat, increasing the thickness of plaster and provide movement joints.

There are 240 cases of peeling and blistering paint and 138 cases were associated with poor design. Moisture, heat, and vandalism from users are the main cause of design failure. Such defects could be avoided if: (1) moisture and heat were blocked off; and (2) materials that could withstand moisture, heat, and vandalism were used.

Of the 672 cases of wall stains, 566 were associated with

Table 3. Summary of Major Internal Wall Defects, Failure Causes, and Design Strategies to Prevent These Defects from Occurring

Major latent defects	Total number	Total by design	Major failure causes	Design strategies
Plaster crack	1,084	748	Moisture from wet areas, impact from occupants, deteriorates faster than expected, weather	Appropriate materials, protection against occupants and loads, prevent water leakage
Stain	672	566	Impact from occupants, moisture form wet areas	
Water seepage	285	125	Weather, moisture from wet areas, deteriorates faster than expected	Appropriate materials, prevent water leakage,
Paint peeling and blister	240	138	Moisture from wet areas, impact from occupants, deteriorates faster than expected, weather	Improve specifications and clarity of design, protection against occupants and loads, prevent water leakage
Paint and plaster patchy	155	0	—	—
Chipped	147	89	Impact from occupants and loads	Protection against occupants and loads, appropriate materials
Concrete and tiles crack	141	89	Moisture from wet areas, weather, impact from occupants	Appropriate materials, protection against occupants and loads
Other types of cracks	111	90	Moisture from wet areas, weather, impact from occupants	
Tiles falling/ popping	94	34	Moisture from the wet areas, weather, impact from occupants	Appropriate materials, prevent water leakage

design failure. These stains were caused by impacts from building occupants, moisture, and heat. Frequent splashing of water on the wall surface accumulated dirt on the wall, and dirt drying off after splashing caused permanent wall staining. Water leakages from adjacent building elements, like ceiling and floor, also stained walls. Such defects could be prevented by stopping moisture from traveling between the wall and other building elements and using darker materials to better hide the stain visually.

One hundred forty seven cases of chipped wall were found and 89 cases were associated with design failure. Most of the chipped defects were found on walls made of soft materials, like fiberboard or gypsum board. These boards were easy prey to vandals and less resistance to impacts. Protection should be installed at corners and edges to reduce vandalism and protect against accidents.

Thirty four out of 94 cases of falling tiles were associated with design failure. Again, moisture, heat, and impacts from occupants caused most of these design defects related to falling tiles. Installing expansion joints at the right locations and changing wall orientations could be possible solutions.

Table 3 summarizes the types of internal wall defects found, the types that were caused by design failure, the failure mechanisms, and design parameters that could be effective in controlling such latent defects.

Brief Discussions on Floor Defects

Eight hundred twenty seven cracks were found on the floor and 638 of these cracks were due to inappropriately specified materials. Three hundred eighty six cases of tiles delamination were due to poor design. Weather and high human and load traffic caused most of the cracks and tiles delamination on the floor. Strong sunlight and moisture introduced by rain caused materials to crack or tiles to delaminate. Grout failure was also very common,

Table 4. Summary of Major Floor Defects, Failure Causes and Design Strategies to Prevent These Defects from Occurring

Major latent defects	Total Number	Total by design	Major failure causes	Design strategies
Cracks	827	638	Weather, self-inflicted by occupants and loads, deteriorates faster than expected, moisture from wet areas	Appropriate materials, protection from occupants and loads, improving design and layout
Water seepage	550	245	Moisture from wet areas, weather	Appropriate materials
Tiles delamination	531	386	Impact from occupants and loads, weather, inflicted by occupants	Appropriate materials, protection against occupants and loads, improving design and layout
Unevenness	461	0	—	—
Stains	347	245	Weather, moisture from wet areas, inflicted by occupants	Appropriate materials, improving design and layout, protection against occupants and loads
Hollowness	168	0	—	—
Discolored tiles	165	115	Weather, moisture from wet areas, inflicted by occupants	Appropriate materials, improving design and layout, protection against occupants and loads
Efflorescence	156	0	—	—
Chipped tiles	61	57	Inflicted by occupants	Protection against occupants and loads, improving design and layout

Table 5. Summary of Major External Wall Defects, Failure Causes, and Design Strategies to Prevent These Defects from Occurring

Major latent defects	Total number	Total by design	Major failure causes	Design strategies
Water seepage	630	393	Weather, moisture form wet areas	Appropriate materials, prevent water seepage
Plaster cracks	475	255		
Strain	314	45	Weather, vandalism, and accidents	Appropriate materials and prevent water seepage,
Paint peeling/blistering	292	50	Weather, moisture from wet areas	Appropriate materials, prevent water seepage
Paint discolored	89	50		
Efflorescent	53	87		
Missing items on curtain wall	22	39	Weather	Appropriate materials

improper expansion joint designs, and frequent expansion and contraction of grouts from the heat and moisture caused grouts to fail.

Some tiles delamination and grout cracks were due to excessive structural movement. Structural designers could prevent the crack and tiles from delamination through better structural design while architects could prevent the cracks and delamination by shielding the areas from weather and specifying materials that can better resist human and load impacts.

Stains were introduced into the buildings by occupants and weather. Occupants' footwear was not properly cleaned when they entered the buildings and thus floors were often stained as a result. On the other hand, moisture introduced into the buildings (either moisture traveling into the building or being brought into the building by the occupants) caused joint colorings to spread and stained other parts of the floor. Designers could have prevented such stains by using darker colored tiles, installing "scrubbing" mats to scrub off dirt from footwear, and provide shielding from the weather and wet areas.

There were 165 cases of discolored tiles and most of the discolored tiles were located near wet areas. One hundred fifteen cases were caused by poor design. Discolored tiles described tiles whose colors had faded or changed. Most of the discolored tiles

Table 6. Summary of Major Door Defects, Failure Causes, and Design Strategies to Prevent These Defects from Occurring

Major latent defects	Total number	Total by design	Major failure causes	Design strategies
Ironmongery unable to function/damaged	330	165	Deteriorates faster than expected, vandalism or accidents, impacts by occupants or loads	Improve specification, use better materials, protection against occupants and loads
Ironmongery rusty	431	216	Wear and tear, weather, deteriorates faster than expected	Improve materials and specifications, improve design and layout
Sagging/inalignment	230	46	Wear and tear or impacts by occupants or loads, vandalism or accidents, deteriorates faster than expected	Improve materials and specifications, improve design and layout, protection against occupants and loads
Timber warp/rot/scratches	220	121	Weather, moisture from the wet areas, deteriorates faster than expected	Improve materials and specifications, improve design and layout
Paint peeling	70	21	Vandalism, impacts by occupants or loads	Protection against occupants and loads
Missing item	72	36	Vandalism	Protection against occupants and loads

Table 7. Summary of Major Window Defects, Failure Causes, and Design Strategies to Prevent These Defects from Occurring

Major latent defects	Total number	Total by design	Major failure causes	Design strategies
Damaged or spoilt ironmongery	699	469	Vandalism, accidents, wear and tear, deteriorates faster than expected, impacts from occupants and loads, weather	Protection against occupants and loads, improve specifications and materials quality, improve design, and layout
Water seepage	694	382		
Misalignment (with/without difficulties in opening)	456	228		
Sealant and gasket damage etc.	240	72	Vandalism, accidents, deteriorates faster than expected, impacts from occupants and loads	Protection against occupants and loads, improve design and layout
Glass stained	40	20	Weather	Improve material quality
No sealant provided	40	40	—[a]	—[a]
Loose panel	29	17	Vandalism, accidents, deteriorates faster than expected, impacts from occupants and loads	Protection against occupants and loads, improve design and layout

[a]Designer failed to provide.

Table 8. Summary of Major Plumbing and Sanitary Defects, Failure Causes, and Design Strategies to Prevent These Defects from Occurring

Major latent defects	Total number	Total by design	Major failure causes	Design strategies
Pipes leakage	407	143	Vandalism or accident, impacts from occupants and loads, deteriorates faster than expected	Improve design and layout, improve material quality, protection from occupants and loads
System/accessories not working	333	287	Vandalism or accident, impacts from occupants and loads, moisture from the wet areas, deteriorates faster than expected	Prevent water leakage, improve material quality and specifications, improve design and layout, protection against occupants and loads
Pipes chokage	179	76	Deteriorates faster than expected	Improve material quality, protection against occupants and loads, improve layout and design
Pipe system etc. damaged	70	39	Vandalism or accident, impacts from occupants and loads, moisture from the wet areas	
Dirty water	64	13	Vandalism	—

Table 9. Summary of Major Roof Defects, Failure Causes, and Design Strategies to Prevent These Defects from Occurring

Major latent defects	Total number	Total by design	Major failure causes	Design strategies
Leakage	222	155	Weather, moisture from wet areas	Improve material quality, prevent water leakage, protection from occupants, and loads
Cracks	87	61	Weather, impacts from occupants and loads	
Water proofing delaminating	67	15	Deteriorates faster than expected, weather	
Stain	65	58	Water moisture from wet areas, impacts from occupants and loads	
Poor thermal insulation	8	8	Weather	Improve material quality

Table 10. Summary of Major M&E Defects, Failure Causes, and Design Strategies to Prevent These Defects from Occurring

Major latent defects	Total number	Total by design	Major failure causes	Design strategies
A/C, including ducts	511	357	Deteriorates faster than expected, impacts from occupants, vandalism or accidents, moisture from the wet areas	Improving specifications, improving design and layout, protection against occupants and loads, improve material quality
Light fittings	308	246	Deteriorates faster than expected, impacts from occupants, vandalism or accidents, moisture from the wet areas	Improving specifications, improving design and layout, protection against occupants and loads, improve material quality
Urinal sensor	53	53	Deteriorates faster than expected, impacts from occupants, vandalism or accidents, moisture from the wet areas	Improving specifications, improving design and layout, protection against occupants and loads
Heating elements	48	48	Deteriorates faster than expected, impacts from occupants	Improving specifications, improving design and layout, improve material quality

Table 11. Summary of Major Ceiling Defects, Failure Causes, and Design Strategies to Prevent These Defects from Occurring

Major latent defects	Total number	Total by design	Major failure causes	Design strategies
Water seepage	492	393	Moisture from wet areas, impacts from occupants or loads, weather	Prevent water leakage, improve material quality, improve specifications
Stain	380	255	Moisture from wet areas, vandalism or accidents, impacts from occupants or loads, deteriorates faster than expected	Prevent water leakage, improve design and layout
Cracks	174	87	Moisture from wet areas, vandalism or accidents, impacts from occupants or loads, deteriorates faster than expected	Prevent water leakage, improve material quality, protection against occupants and loads
Fungus/algae	45	39	Moisture from wet areas, weather	Prevent water leakage, improve specifications

were due to high heat and moisture exposure and several were caused by abrasions from occupants' footwear and loads.

The analyses for all the elements were summarized in Tables 1–11. Major defects found from all the elements were documented in Tables 3–11 while Tables 1 and 2 provide overall distributions of design parameters and failure mechanisms for different elements.

Design Strategies and Latent Defects Prevention Methods

Weather, moisture from wet areas, wear and tear, and impacts from occupants and loads, vandalism or accidents, and poor quality materials leading to faster than expected deterioration were the top five failure causes that resulted from poor design. Five design strategies, like using materials that are more appropriate for the conditions, protecting elements against impacts from the occupants and loads, preventing water leakage, improving specifications, and clarity of design, and changing design and layout of the buildings could prevent the triggering of these defects. Failure causes are further broken down to allow designers a better understanding of how they worked.

Weather

Weather related defects were caused by: (1) heat and ultraviolet rays from the sun; (2) moisture from the rain; (3) humidity in the air; and (4) wind loads. Sun is the biggest heat source. Heat encourages expansion and when heat source is removed or moisture is introduced to cool materials, contraction occurs. Frequent expansion and contraction increase stress in materials, and without a proper defense system, such stress will cause cracks and fracture at the weakest point. The most common defense system against expansion and contraction is the expansion joint. It is an effective system but it often encourages moisture and dirt infiltration. It must be accompanied by a proper moisture and dirt dispelling system to get rid of both moisture and dirt. Weep holes or flushing can be installed near these expansion joints to dispel water and dirt. In areas where installation of weep holes and flushing are impossible, materials that discourage accumulation of moisture and dirt should be used.

The resulting effects from combining moisture and heat can be devastating and attempting to stop both at one time can be very difficult. Isolating one while solving the other can be an effective solution. For example, walls can be reorientated to avoid direct contact with heat and the designer can then concentrate on designing details to dispel moisture. Designers also need to consider wind effects on moisture penetration so that their proposed moisture disposal system can function more effectively.

Humid air caused many problems like moisture condensation and staining. Using materials and a system that can resist moisture and stain can prevent triggering the mechanism. Proper ventilation can also help control air humidity.

Moisture from Wet Areas

The presence of moisture in wet areas also triggered several moisture related defects. Capillary action pushes moisture into dry areas. Properly installed and designed waterproofing can prevent moisture from traveling into dry areas. However, there are many poorly installed waterproofing projects that designers had no control over. Installing a moisture stopper between the wet and dry area can help to stop traveling moisture. Moisture absorbing carpets can be installed on the wet area just before the dry area (commonly used in homes) to prevent moisture from getting into the dry area. An intermediate zone can be placed between wet and dry areas to act as a moisture trapping zone and moisture traveling from the wet area cannot reach the dry area if the zone is sufficiently long.

Leaking pipes were also very common. Leaks from pipes often caused staining on ceilings and floors. These leaks penetrated the wall and traveled to dry areas. Designers can help control the impact of this workmanship defect by installing a leakage stopping system to stop the leaks from flowing further. A zone that allows water from the leaking pipes to accumulate leaking water can be positioned in such a way to prevent leaks from flowing into dry areas.

Impacts from Occupants and Loads

Defects from impacts from occupants and loads were often due to inadequate design provisions. For example, wall edges were found to chip due to impacts of loads and occupants. Installing metal or rubber protections on edges of walls in locations with high human and load traffic could prevent such defects. In the long run, the cost of edges protection can be significantly lower than the cost of repair to damaged edges.

Designing a zone to trap dirt and moisture from occupants' footwear before they enter buildings can help prevent staining. Carpets and dark colored tiles can be used to scrape off dirt and hide stains, respectively. Materials that can better resist abrasion should be used in areas with high wear and tear.

Vandalism and Accidents

Softer building materials often invite vandalism. Wood, gypsum board, softwood ceilings, and noise barriers made of resin were common targets as scratches, cracks, and holes were found in these materials. Most of these defects occurred on wall surfaces. Installing harder materials and designing a zone to distance occupants from these materials can reduce the tendency of vandalism and accidents. Installation protection on the edges can help to reduce the number of such defects.

Material Quality Not Up to Expectations

Materials were also found to deteriorate faster than expected. These materials failed before their intended lifespan. Although many were due to poor workmanship, most of these defects could have been prevented with better design detailing, specifications, and using more appropriate materials.

Structural and Geotechnical Problems

There were comparatively fewer structural and geotechnical defects. However, the impacts of such defects were devastating. Two buildings were affected by differential soil settlement (most likely due to expansive clay) and structural cracks were found on floors and walls as a result. The foundation and geotechnical engineers were blamed for causing such defects. Structural engineers were called in to conduct a structural survey and found that the cracks were not serious and that the structural frames had sufficient strength to support the entire building. Such defect can only be prevented with better geotechnical inputs by conducting more tests and using statistical interpolation of soil tests conducted in other surrounding buildings to estimate soil conditions.

Underdesigned beams and slabs was also found in one building as spalling concrete was found in three beams and one column.

Structural and geotechnical problems can only be resolved with better design and tests. However, these defects were rare in Singapore. Structural and geotechnical engineers should continue to upgrade their knowledge to improve their designs.

Conclusion

This research shows that it is possible to design a simple and flexible decision framework that designers can rely on for design evaluation and to eliminate latent defects from their designs. There are too many defects and designers are unable to eliminate all of them effectively. Many designers are not aware of standards and codes, like the American Standard for Testing of Materials (ASTM), British Standard (BS), and Singapore Standards (SS). Many defects continue to be repeated in every building as designers failed to obtain important feedback from property managers on these defects. This research confirmed designers can improve overall building quality by consolidating efforts on a few major defects and gathering existing knowledge from the property managers. Designers are also encouraged to adopt and refer to existing regional standards since there are many solutions in these standards and codes.

Cost and other design issues should be just as important as eliminating latent defects. Designers should also be encouraged to explore new knowledge and technologies. Other than referring to existing standards, designers should be encouraged to explore new ideas and they should rely on existing knowledge of the property managers to identify problematic areas of their designs that current standards and codes fail to provide for. Developing a database and decision framework can also help simplify the process of identifying defective designs.

It is impossible to identify all types of latent defects without a good information source to rely upon. Designers often rely on their own experience, some employ consultants, and a few have some sort of database of past defects to guide them. But experience and research showed that many latent defects were repeated in many of the buildings and designers were not aware of that. We must appreciate that it is impossible to eliminate all latent defects in a building. However, it is possible to eliminate most latent defects through better design only if the designers know about them. Designers are encouraged to keep a database whereby latent defects could be traced and mistakes avoided in their next design. Such a database can be developed with existing standards and from property managers.

However, new materials and technologies emerged every now and then and the performance of these materials and technologies have never been properly evaluated and documented. It is therefore proposed that a database be built which the construction industry can use to better identify latent defects. Such a database could be maintained by a governmental agency or private organization with access allowed by designers during the design stage and they can be incorporated into existing codes and standards at a later stage. Existing research found that designers lacked the necessary knowledge on the impact of their design on latent defects. However, this research found that good property managers can also be an extremely good source for such information.

A fully automated design–check system could be developed to check for defective designs automatically. New generation computers are able to carry such functions, given appropriate software architecture and algorithms. Further research should be carried out to examine the possibility of developing such a system. Future research can also look into how designers can better exploit the knowledge of the property managers and how to encourage property managers' participation at the design stage. Future research can also look into identifying particular standards that these defects could have been prevented with and to determine whether these defects have been covered by existing standards.

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