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Defects of Tensioned Membrane Structures (TMS) in the Tropics

ABSTRACT

The wide use of tensioned membrane structures (TMS) becomes prominent in many designs because of its aesthetic, ergonomic, and economical nature. Recently, TMS has been applied in the tropics with success, yet defects specific to this region have received little attention. Through a questionnaire survey of 890 uses and technicians of TMS in three different areas in Malaysia, this study identified the most frequently occurring TMS defects in the tropics, such as "deterioration of roof coatings", "corrosion or fatigue in fixings", "fungal decay, mould growth, and dirt in membrane", "corrosion in anchor cables", and "degradation of fabrics". These defects are quite different from those in other climatic zones. The top five causes of TMS defects in the tropics are weather, aging, design, construction/installation, and material selection. However, only "corrosion or fatigue in fixings" is a significant predictor for "deterioration of roof coatings". While this is not a causal effect, a practical implication is that TMS maintenance workers do not have to climb up to the roof to check the deterioration in coating but only need to predict the deterioration through the corrosion levels of the fixings. Further, seven countermeasures for TMS in tropic are recommended. This study is the first comprehensive study examining tensioned membrane structure defects in the tropics.

Keywords: tensioned membrane structure, defects in TMS, membrane structure, tensioned structure, deterioration of roof coatings

Introduction

Nowadays, the wide use of tensioned membrane structures (TMS) has featured prominently in many architectural designs because of its aesthetic and ergonomic nature (Tan, 2011; Gosling et al., 2013a). Tensioned membrane structures are part of a developing technology which gives designers, architects and engineers the ability to experiment with form and creates exciting new solutions to conventional design problems (Toyoda & Takahashi, 2013; Shaeffer, 1996). TMS is not only visually exciting but also environmentally sensitive and economically competitive (Guo, 2008; Habib & Rokonuzzaman, 2011). While the first TMS was built by the Russian engineer Vladimir Shukhov in the Nizhny Novgorod Fair in 1896, the modern era of TMS is considered to have begun with a small bandstand designed and built by Frei Otto for the Federal Garden Exhibition in Cassel, Germany in 1955. Otto was a key pioneer in the development of tensile structures and he inspired many others to use TMS (Shaeffer, 1996). The approach integrates structural mechanicals, architecture, chemistry, and material science. Recently, TMS has been used in the tropics to construct a variety of structures including stadiums, exhibition halls, shopping complexes, convention centers, amphitheatres, community halls, and transport terminals (Toyoda & Takahashi, 2013; Gosling et al., 2013b). In Malaysia, the largest membrane structure built was the Bukit Jalil Sports Complex, completed in 1998 for the Commonwealth Games. However, Supartono (2011) argued that defect can occur in TMS due to the flexible nature coupled with improper installation or by mistakes in the membrane cutting or pattern design. A cracked membrane surface may induce higher stress in other parts of the membrane surface (Huntington, 2009). Defects may also occur due to weather conditions (e.g., strong winds or rain during the installation of pre-tensioning). As weather patterns in the tropics are different to other regions, these unique conditions of moisture, temperature, and solar radiation mean that the types and causes of TMS defects in the tropics may differ from other climatic zones (Gosling et al., 2013b; Tian, 2011; Supartono, 2011). The aim of this research is to identify the types and causes of defects in TMS erected in the tropics and to identify key measures to improve future use and maintenance of TMS in tropical regions.

Tensioned Membrane Structures (TMS) and Applications

TMS is a spatial shape formed by interior pretension from multiple strong and thin membrane materials (e.g., polyvinyl chloride (PVC)) and reinforcement members (e.g., a steel structure, steel posts, or steel cable) (Foster, 2000; Toyoda & Takahashi, 2013). The tensioned membrane structure is put into tension using either of two methods. Materials can be stretched materials over compression supports and anchored either to the ground or to the heads of shorter braced columns (in the manner of the traditional circus tent on its poles); alternatively, the membrane structure can be suspended using tension supports (usually cable hangers) and then anchored to the ground (Foster et al., 2007). TMS currently represents the mainstream of membrane design and construction. Due to the pleasing aesthetics, designers favor the use of a curved shape for TMS. The tension is induced in the membrane in addition to any self-weight and live loads they may carry, with the objective of ensuring that the usually flexible structural elements remain stiff under all working loads (Supartono et al, 2011). The level of pretension determines the shape of membrane structure and tension can be applied to the membrane structure by stretching from its edges or by pre-tensioning the cables which support the membrane and therefore change its shape (Supartono et al., 2011). The internal force path of TMS is more complex than found in frame structures so that the structural design, cutting pattern design, and the installation of TMS must be completed with high precision.

There are two other types of membrane structures in addition to TMS, namely: pneumatic structures (e.g., air stabilized; also known as air-supported or air-inflated membrane structures) and frame membrane structures (Brew & Lewis, 2013). Pneumatic structures rely on air pressure being continuously created within the membrane structure to inflate the membrane until it becomes stiff enough to support its own weight and any surface loads. Frequently, a pressure of approximately 3/1000 higher than the atmospheric pressure must be applied and should remain constant during operation (Supartono et al., 2011). The frame membrane structure is composed by a self-stable frame that is covered with a membrane. The frame structure can be steel frame, steel space frame, or space truss. The membrane should be calculated as a plane stress element so that the external loads are carried by tensile stresses induced in the membrane surface only, referred to as 'membrane stresses' (Supartono et al., 2011).

Materials used in TMS

TMS is also known as a 'fabric structure' because it is made of fabric and tensioned membrane elements. The fabric or membrane elements make TMS unique and distinct from other structures (Supartono, et al., 2011). Membrane materials commonly consist of PVC, PTFE (polytetrafluoroethylene), HDFE (high-density polyethylene), and ETFE (ethylene tetrafluoroethylene) (Nunes, 2012).

PVC (Polyvinyl chloride)

PVC is a translucent fabric which has been widely used for over 20 years for membrane structures. The fabric is composed of high strength fibers such as polyamide, polyester, or polyvinyl; resistance to ultraviolet (UV) rays can enhanced by the addition of white pigments (Gosling et al., 2013a).

PTFE (polytetrafluoroethylene)

This material is based on a glass fiber cloth and surface lining of polytetrafluoroethylene (PTFE); no surface treatment is required when used as a membrane material as PTFE is chemically very stable (Supartono et al., 2011). Generally, PTFE has better strength, durability, and self-cleaning performance than PVC membranes, but is more expensive. PTFE has high fire resistance; a lifespan exceeding 25 years; it is unaffected by UV rays; is chemically inert but bleaches white when exposed to sunlight; limited colors are generally available, although specific hues can be custom-made; and it has around 25% translucency, which provides a diffused light in the interior and reduces the need for supplementary lighting.

ETFE (Ethylene tetrafluoroethylene)

ETFE is created from a thin layer of ethylene tetrafluoroethylene. When used in a membrane, this material is much more transparent than PVC or PTFE membranes due to the thinness of the layer (with a transparency rate of 90%). This transparency means that it can, to an extent, replace glass as a transparent roofing material (Supartono et al., 2011); however, ETFE has less strength than other materials and usually requires a base fabric for additional support. ETFE is more applicable in the frame membrane structure or air supported membrane structure than TMS.

HDFE (high-density polyethylene),

HDFE fabric is a cost effective material designed for basic modular structures. HDFE is suited to large commercial projects where specifications require the fabric to be exposed to environmental conditions including wind, rain, dust, and UV exposure (Nunes, 2012).

In the tropics, the frame and cables of TMS are constructed of steel. Protection against corrosion is accomplished by adding a clear PVC coat to the cables and a smooth layer of powder coat over a base of primer for the frames. The materials carry loads are mainly through tensile stresses. The materials used for TMS in the tropics possess the following characteristics: a) high strength, b) good heat insulation, c) sound insulation, d) low flammable rates, and e) self-cleaning.

Parts of TMS in Construction

There are four key elements that must be considered in when designing or constructing TMS: membranes, anchorages, cables and ropes, and access openings.

Membranes

Membranes are normally made of highly tensioned fabrics but may also be constructed of coated fabrics, plastic films, woven metallic fabrics, or metallic foils (Gosling et al., 2013b). The fabrics consist of a terylene or nylon fabric coating on one or both sides with a plasticized elastomer (e.g., neoprene or vinyl), or of woven glass fibre coated with Teflon or silicone (Foster et al., 2007). There are single tent membranes, most suitable for areas which do not need heating habitable standards; alternatively, two-skin membranes with wool or mineral fibre insulation can provide greater thermal insulation (Seidel, 2009). Moreover, there are tubes in air inflated tube structure which are commonly in the form of a circular woven fabric sleeve with an inner airtight elastomer lining and an outer weather resistant coating of similar materials (Pargana et al., 2008). The method of joining membranes together depends on the specific materials used; frequently, the joins between membranes are achieved using a sewn double-folded seam, cementing, or heat welding.

Anchorages

Anchors are used to secure a membrane or a cable to supporting masonry. Direct or positive anchorage into the ground is used for membrane structures that are to be in position for long periods of time (Loong et al., 2007). This allows the TMS to be secured over the perimeter to a continuous concrete foundation. The bottom edge of the membrane can be ended with a rope welt which may be clamped to a continuous timber cill piece either using coach screws or bolts passing through steel angles, or timber battens; the cill piece is rag bolted at intervals to the concrete strip foundation (Gosling et al., 2013b). Other methods of positive anchorage involves the use of pipes or cables, accommodate in fabric sleeves or hems attached to the membrane, which are secured to anchors at intervals round the perimeter. There are two types of anchors for tent structures. First, pipes are inserted in a hem round the base of the membrane, allowing these to be attached to ground anchors at cut-outs in the hem at 1m intervals. Alternatively, the rope or cable can pass through shaped fabric sleeves sewn into the base of the membrane, allowing it to be secured at intervals to the ground anchors (Foster et al., 2007).

Cables and Ropes

TMS uses steel, nylon, or polyester cables to divide air supported membranes into smaller elements. Chafing or friction from small movements can cause wear on the membrane as the two components move relative to each other. This problem can be solved by placing cables internally and then attaching the membrane to them using dropped skirts and lacing (Foster et al., 2007). The ridge and valley cables cause the chafing in tent structures. This can be avoided by carefully placing the cable externally along the ridge line and linking the membrane to it using metal connectors (Loong et al., 2007; Beatini & Royer-Carfagni, 2013)

Access Openings

TMS requires air locks or air curtains. There is a vane to provide a counterbalance and to make opening easy.

Features, Advantages, and Applications of TMS

Common features of TMS that make it popular include its: a) transparency, b) light-weight structure, c) fire resistance and durability, d) self-cleaning properties, and e) large spans with open spaces.

Transparency - The transparency of the materials contributes to the creation of a bright space illuminated by natural light. The sunlight allows the building to be full of natural and diffuse light in the daytime. At night, interior lamp light permeates the TMS membranes to increase illumination of nearby night scenery. When the membrane is used in gymnasium and entertainment facilities, a large space can be achieved with continual lighting throughout the day and suitable commercial spaces established for comfort can be created.

Light-weight structure- TMS has the potential to contribute to disaster prevention and relief efforts as TMS materials are generally lighter than other constructional materials. Membrane materials in the roofing contribute to the strong aseismatic performance and safety characteristics of TMS (Gosling et al., 2013a). During disasters, temporary refuge, emergency rescue center gymnasiums, and disaster relief command centers can be created using multifunctional TMS facilities, providing lots of useable spaces.

Fire resistance and durability- TMS buildings with PTFE or PVC membranes are characterized by high levels of heat and fire resistance, weather resistance, drug resistance, and high strength. The materials age well and can be maintained to keep their initial strength even after long periods of use.

Self-cleaning properties- The surface painting of the PTFE membrane material is polytetrafluoroethylene resin, the same surface coating used on most non–stick cookware. The surface of the PTFE tensioned membrane materials resists dirt and dust coatings; any build-up that occurs can be easily cleaned away by rainwater. This creates a low-maintenance and easily cleaned surface.

Large spans with open spaces - The membrane material for the membrane structural building is very light, at about 1kg per square meter. TMS can create huge, non-column spaces, providing open areas of significant size.

Tian (2011) listed the following advantages of TMS: a) aesthetic and translucent, b) cost effective to provide roofing to either new or existing areas, c) low maintenance compared to glass, d) able to disperse natural light with condensed heat load (excellent alternative to polycarbonate or glass as roof glazing system), e) absorbs solar energy (4%-17%) and reduces the heat load, f) higher transmission of light during daytime (sufficient to reduce artificial lighting requirements by 5-20%), g) larger span for more coverage, h) no extension joints as the membranes structures are welded into a single weatherproof skin, i) minimal site interruptions since the membranes structures are manufactured in factories before being transported to site for assembly, and j) suitable for rapid construction on site.

Applications of TMS in building facilities (Nunes, 2012; Supartono et al., 2011; Shaeffer, 1996) include: a) sport facilities; e.g., stadiums, gymnasiums, fitting centers, basketball courts, swimming pools, and tennis courts; b) transportation facilities; e.g., bus stations, airports, railway stations, toll stations, ports, gas filling stations, and elevated corridors; c) commercial facilities; e.g., malls, hotels, restaurants, shopping centers, and commercial street-side facilities; d) industrial facilities; e.g., in a factories, warehouses, green houses, sewage treatment centers, scientific research centers, and logistics centers; e) landscape facilities; e.g., landscape works, park works, building entrances, music plazas, beach entertainment and leisure buildings, community spaces, parking lots, and amusement plazas; f) interior building; e.g., decorations, halls, interior models, and entrances; and g) flagship building; e.g., exhibition halls, entrance landmarks, urban and regional landmark.

Defects in TMS

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A building is considered as defective when there are shortcomings or failings in the function, performance, or statutory or user requirements of a building. These may be apparent within the structure, fabric, services, or other facilities of the affected building (Khoo, 2011; Campbell, 2001; Low & Wee, 2001; Li & Yuan, 2013). Defects in TMS can be split into three categories (Sommerville & McCosh, 2007): a) aesthetic, when a building element or material is unfavorably affected or fails to be visually pleasing; b) functional, when a building fails to perform its intended function or manner; and c) technical, when the workmanship, design, or materials of an element decrease its capacity to functionally perform. Table 1 lists some common types of defects in TMS together with the relevant authors.

Table 1: Types of defects in TMS

Type of Defects	Authors
Membranes/fabrics i. Fabric tearing i. The fabric may be folding or scratched i. Wrinkling of fabric v. Flapping and fluttering of the fabric v. Degradation of fabric i. Fungal decay, mould growth, and dirt in membrane	Shaeffer (1996); Foster (2007); Foster (2000); Cheng (2007); Supartono et al. (2011); Gosling et al. (2013a)
Anchorage i. Corrosion in anchor cables i. Deflection of anchors	Cheng (2007); Foster (2007); Foster (2000)
Cables/ropes i. Slack or drooping cable/ropes i. Corrosion in cables	Shaeffer (1996); Foster (2007); Cheng (2007); Tian (2011); Gosling et al. (2013b)
Mast/pole	Foster (2000); Cheng (2007)

i. Deflection of the mast i. Change of mast position	
Rings and arches i. Corrosion of the rings and arches	Macdonald (2001); Shaeffer (1996); Foster (2007); Cheng (2007); Gosling et al. (2013a)
Fixings i. Corrosion or fatigue in fixings	Tian (2011); Foster (2000); Li & Yuan (2013)
Foundation i. Cracks in foundations	Shaeffer (1996); Macdonald (2001)
Roof i. Deterioration of roof coatings	Cheng (2007); Shaeffer (1996); Macdonald (2001); Foster et al. (2007)
Services i. Lighting breakdown i. Lack of water drainage and pooling of water	Foster et al. (2007); Foster (2000); Supartono et al. (2011)

Sommerville (2007) states that design problems contributed to 50% of the defects found in construction projects, 40% of defects occurred during the construction process and 10% could be attributed to the failure of materials. Many authors have discussed the various causes of defective works in construction industry and Table 2 shows the categories of causes of building defects.

Table 2: Causes of defects in buildings

Causes of Defects	Authors
Weather	Shaeffer (1996); Richardson (2001); Low & Wee (2001); Cheng (2007)
Design	Richardson (2001); Low & Wee (2001); Cheng (2007)
Construction/ installation process	Foster et al. (2007); Richardson (2001); Cheng (2007)
Aging	Richardson (2001); Cook & Hinks (1992)
User involvement	Richardson (2001); Cheng (2007)
Cost pressure	Foster et al. (2007); Low & Wee (2001)

Workmanship	Richardson (2001); Low & Wee (2001)
Material selection	Shaeffer (1996); Foster et al. (2007); Richardson (2001); Cheng (2007),
Fabrication techniques	Cheng (2007); Ilozor et al. (2004)
Lack of quality	Shaeffer (1996); Cheng (2007)

Research Design and Methods

A questionnaire or survey is a good method to overcome the challenge of working with a large population and to gain data from various individuals (Khoo, 2011); thus, a questionnaire was employed in this study. We selected three areas in Klang Valley (Malaysia) where TMS is a commonly used building style: Amphitheatre in University of Malaya, Alamanda in Putrajaya, and Central Market in Kuala Lumpur. 890 questionnaires were distributed to TMS users andt his resulted in 96 respondents who provided complete and valid feedback (a response rate of 10.79 %). Table 3 shows the numbers and percentages of respondents in these three areas in Klang Valley. The respondents' demographic profiles are further illustrated in Table 4.

Table 3: Distribution of respondents by areas

TMS	Number of the respondents	Percentage (%)
Amphitheatre in University of Malaya	45	46.88
Alamanda in Putrajaya	24	25.00
Central Market in Kuala Lumpur	27	28.12
Total	96	100.00

There are three main ethnic groups in Malaysia: Malay, Chinese, and Indian. Among the 96 respondents, 61.5% were Malays, 22.9% were Chinese, 11.5% were Indians, and 4.2% were foreigners staying in Malaysia (e.g., Indonesian, Iranian, and Sudanese); this roughly representative with the ethnic mix of the wider population in Malaysia. The number of male (52.1%) and female (47.9%) respondents were roughly equal. Most respondents were below 31 years old with 78.1% of respondents between 18 to 25 years old. Only 4.1% respondents were older than 40. Most respondents were educated at the Tertiary level (94.8%). Among these 96 respondents, 19.8% were TMS technicians who installed and maintained the TMSs and 66.7% were daily users of TMSs. The other 13.5% were occasional users of these TMSs.

Table 4: Respondents' Profiles

Social-demographic characteristics	Frequency (n=96)	Valid Percentage	Cumulative Percentage
Gender			
• Male	50	52.1	52.1
• Female	46	47.9	100.0
Race			
• Malays	59	61.5	61.5
• Chinese	22	22.9	84.4
• Indians	11	11.5	95.8
• Others	4	4.2	100.0
Age			
• 18-25 year old	75	78.1	78.1
• 26-30 year old	10	10.4	88.5
• 31-40 year old	7	7.3	95.8
• 41-50 year old	3	3.1	99.0
• More than 50 year old	1	1.0	100.0
Education level			

• Primary	1	1.0	1.0
• Secondary	4	4.2	5.2
• Tertiary	91	94.8	100.0
Type of User regarding TMS			
• TMS technicians	19	19.8	19.8
• Daily Users	64	66.7	86.5
• Occasional Users	13	13.5	100.0

The questionnaire form was designed with three sections. Section A captures the profiles of respondents and Section B identifies common types of TMS defects found in the tropics and how frequently these occur. A four-level rating scale was used for the frequency of each type of defect (viz., never, rare, frequent, and very frequent). Section C captured data on the causes of defects, where the respondents had to identify causes of defects; e.g., weather, design, installation process, aging, user involvement, time pressure, cost pressure, workmanship, material selection, and fabrication techniques. Respondents were allowed to select multiple causes in this section.

The data were analyzed using Cronbach's alpha, frequency analysis, scale index analysis, Pearson's correlation, regression tests, and one way ANOVA. Since a relative high value of Cronbach's alpha is commonly used as evidence that particular items measure an underlying construct, Cronbach's alpha test was used to identify the internal consistency of items in this survey to gauge the reliability. Pearson's correlation coefficient was used to measure the strength of relationship between pairs of variables. It is often signified by r (rho) and the value ranged from -1.0 to 1.0. A coefficient of -1.0 indicates perfect negative correlation, 0.0 indicates no correlation, and 1.0 shows perfect positive correlation (Pavkov and Pierce, 2007). The multiple regressions were specifically used in this research to find appropriate indicators of a defect that can be used in maintenance operations. One way ANOVA allowed us to compare the means of unrelated samples.

Data Analysis and Interpretations

Reliability Test Result for Variables

The statistical result of Cronbach's values identified the consistency of the 18 variables in the questionnaire form. The Cronbach's alpha coefficient at 0.840 revealed a reasonable level of internal consistency; values in excess of 0.8 are considered acceptable (Bryman & Cramer, 2001). Table 5 lists the reliability for the measures of all 18 types of defects that occur in TMS in the tropics.

Table 5: Item-total Statistics

No	Type of Defects	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
1	Fabrics tearing	42.18	38.463	.342	.837
2	The fabric may folding or scratched	42.18	38.105	.411	.833
3	Wrinkling of the fabric	42.17	37.172	.503	.829
4	Flapping and fluttering of the fabric	42.23	36.936	.485	.830
5	Degradation of fabric	42.08	37.677	.500	.829
6	Fungal decay, mould growth, and dirt in membrane	42.00	38.063	.403	.834
7	Corrosion in anchor cables	42.02	37.136	.491	.829
8	Deflection of anchors	42.24	36.184	.563	.825

9	Slack or drooping cable/ropes	42.24	38.226	.400	.834
10	Corrosion in cables	42.13	37.774	.454	.831
11	Deflection of the mast	42.28	36.857	.514	.828
12	Change of mast position	42.35	37.873	.393	.834
13	Corrosion of the rings and arches	42.11	36.334	.612	.823
14	Corrosion or fatigue in fixings	41.99	38.179	.390	.834
15	Cracks in foundations	42.26	36.658	.466	.831
16	Deterioration of roof coatings	41.93	36.974	.469	.830
17	Lighting breakdown	42.41	39.507	.210	.843
18	Lack of water drainage and pooling of water	42.19	39.480	.219	.842

Frequency of TMS Defects in the Tropics

We determined the five most frequently occurring defects in tropical TMS. Table 6 illustrates the frequency rankings of these defect types. The highest mean value is 2.72 ("deterioration of roof coatings"), indicating the most frequently occurring TMS defect in the tropics, closely followed by "corrosion or fatigue in fixings" with the second highest mean value (2.66). "Fungal decay, mould growth, and dirt in membrane" was ranked third (mean value of 2.65). The fourth and fifth most common defects are "corrosion in anchor cables" and "degradation of fabrics", respectively.

Table 6: Frequency Ranking of Defects in TMS in Tropic

Type of Defects	Never		Rarely		Frequent		Very Frequent		Mean	Standard Deviation	Rank
	Frequency	(%)	Frequency	(%)	Frequency	(%)	Frequency	(%)			
Membranes/fabric											
Fabrics tearing	5	5.2	46	47.9	40	41.7	5	5.2	2.47	0.68	10
The fabric may folding, scratches	3	3.1	50	52.1	38	39.6	5	5.2	2.47	0.65	9
Wrinkling of the fabrics	5	5.2	45	46.9	41	42.7	5	5.2	2.48	0.68	8
Flapping and fluttering of the fabrics	7	7.3	49	51	33	34.4	7	7.3	2.42	0.74	12
Degradation of fabrics	3	3.1	39	40.6	51	53.1	3	3.1	2.56	0.61	5
Fungal decay, mould growth, and dirt in	3	3.1	35	36.5	51	53.1	7	7.3	2.65	0.67	3

membrane										
Anchorages										
Corrosion in anchor cables	3	3.1	39	40.6	45	46.9	9	9.4	2.63	0.7	4
Deflection of anchor	8	8.3	48	50	33	34.4	7	7.3	2.41	0.75	14
Cables/ropes										
Slack or drooping cable/ropes	4	4.2	53	55.2	35	36.5	4	4.2	2.41	0.64	13
Corrosion in cables	3	3.1	45	46.9	43	44.8	5	5.2	2.52	0.65	7
Mast/pole										
Deflection of the mast	7	7.3	53	55.2	30	31.3	6	6.3	2.36	0.71	16
Position changed of mast	11	11.5	49	51	33	34.4	3	3.1	2.29	0.71	17
Rings and Arches										
Corrosion of the rings and arches	6	6.3	37	38.5	49	51	4	4.2	2.53	0.68	6
Fixings										
Corrosion or fatigue in fixings	2	2.1	37	38.5	49	51	8	8.3	2.66	0.66	2
Foundation										
Cracks in foundation	12	12.5	42	43.8	35	36.5	7	7.3	2.39	0.8	15
Roof										
Deterioration of roof coatings	2	2.1	38	39.6	41	42.7	15	15.6	2.72	0.75	1
Services										
Lighting breakdown	12	12.5	51	53.1	31	32.3	2	2.1	2.24	0.7	18
Water drainage and ponding	6	6.3	44	45.8	42	43.8	4	4.2	2.46	0.68	11

Pearson Correlation among Defects

Pearson correlation was used to examine whether there is inter-correlation between the five most frequently occurring defects in tropical TMSs. The strength of relationship value "r" for Pearson correlation was defined by Weinberg and Abramowitz (2002) as a) no relationship if $0 \leq r < 0.1$; b) a weak relationship if $0.1 \leq r < 0.3$; c) a moderate relationship if $0.3 \leq r < 0.5$; and d) a strong relationship if $r \geq 0.5$. As illustrated in Table 7, a strong correlation between "degradation of fabrics" and "fungal decay, mould growth, and dirt in membrane" (r =0.521) was found at the 0.01 significance level. There were two moderate relationships identified: first, between "deterioration of roof coatings" and "corrosion or fatigue in fixings" (r = 0.333); second, between "deterioration of roof coatings" and "degradation of fabrics" (r = 0.302). Both were significant at the 0.01 level. The other relationships were weak ($r < 0.3$).

Table 7: Pearson correlation among the five most frequently occurring TMS defects in the tropics

		Deterioration of roof coatings	Corrosion or fatigue in fixings	Fungal decay, mould growth, and dirt in membrane	Corrosion in anchor cables	Degradation of fabrics
Deterioration of roof coatings	Pearson Correlation	1	Moderate	Weak	Weak	Moderate
	Sig. (2-tailed)					
	N	96				
Corrosion or fatigue in fixings	Pearson Correlation	.333**	1	Weak	Weak	Weak
	Sig. (2-tailed)	.001				
	N	96	96			
Fungal decay, mould growth and dirt in membrane	Pearson Correlation	.284**	.223*	1	Weak	Strong
	Sig. (2-tailed)	.005	.029			
	N	96	96	96		
Corrosion in anchor cables	Pearson Correlation	.218*	.264**	.255*	1	Weak
	Sig. (2-tailed)	.033	.009	.012		
	N	96	96	96	96	
Degradation of fabrics	Pearson Correlation	.302**	.300**	.521**	.227*	1
	Sig. (2-tailed)	.003	.003	.000	.026	
	N	96	96	96	96	96

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Identifying Predictor Variables

Normally, the roof of a TMS is difficult to assess due to the nature of the structure. Perhaps this is partly the cause of "deterioration of roof coatings" being the most common type of defect as it is not checked as frequently as it should be. However, the situation indicates that if there were a useful measure that could be made that would indicate the presence of deterioration in the roof coatings, then maintenance staff would only need to check the roof if there were a suspicion that a check may be required; if the predictor variable indicated that there were no problems then the difficult check of the roof could be avoided. Multiple regression is commonly used to explore relationships between one continuous dependent variable and a number of independent variables so that a predictor can be found. In this study, the regression test examined whether the most frequently occurring TMS defect ("deterioration of roof coatings") has a linear relationship with the second, third, fourth, or fifth most common defects. Table 8 shows the model summary, showing the percentage of variability in the dependent variable accounted for by all independent variables. This table provides the "*R*" value which indicates how well the regression model fits the data. The "*R"* is a measures the quality of the prediction. In this case, the value of 0.424 indicated a moderately good level of prediction.

Furthermore, Table 9 shows the statistical significance of ANOVA in multiple regressions. The *F*-test indicates whether the model is a good fit for the data according to the *p*-value. In this case, the independent variables significantly predicted the dependent variable, $F\ (4, 91) = 4.974$, $p < 0.001$. The coefficients for the dependent variables are shown in Table 10. The coefficient for "corrosion or fatigue in fixings" at 0.269 is significantly different from 0 because its p-value is 0.022 (i.e., $p<0.05$). However, the coefficients for the other variables are not significant ($p>0.05$); therefore, only "corrosion or fatigue in fixings" is valuable as a predictor for the tropical TMS defect "deterioration of roof coatings". While we cannot take this as a causal effect, the correlation does indicate that in practice, TMS maintenance staff do not have to climb up to the roof to check the deterioration of the coating; rather, they need only predict the deterioration of the coating by measuring the corrosion levels of the fixings.

Table 8: Model Summary for Dependent Variable

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.424[a]	.179	.143	.694

a. Predictors: (Constant), Degradation of fabrics, Corrosion in anchor cables, Corrosion or fatigue in fixings, Fungal decay, mould growth, and dirt in membrane
b. Dependent Variable: Deterioration of roof coatings

Table 9: ANOVA for Dependent Variable

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	9.582	4	2.396	4.974	.001[b]
	Residual	43.824	91	.482		
	Total	53.406	95			

a. Dependent Variable: Deterioration of roof coatings

b. Predictors: (Constant), Degradation of fabrics, Corrosion in anchor cables, Corrosion or fatigue in fixings, Fungal decay, mould growth, and dirt in membrane

Table 10: Coefficient for Dependent Variable

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower Bound	Upper Bound	Zero - order	Partial	Part	Tolerance	VIF
1	(Constant)	.910	.419		2.171	.033	.077	1.742					
	Corrosion or fatigue in fixings.	.269	.115	.237	2.329	.022	.040	.498	.333	.237	.221	.867	1.153
	Fungal decay, mould growth, and dirt in membrane.	.152	.127	.135	1.197	.234	-.100	.405	.284	.125	.114	.708	1.413
	Corrosion in anchor cables.	.096	.108	.089	.884	.379	-.119	.310	.218	.092	.084	.886	1.129
	Degradation of fabrics.	.172	.140	.140	1.229	.222	-.106	.450	.302	.128	.117	.690	1.449

Causes and Countermeasures of TMS Defects in the Tropics

In this section, respondents could choose more than one option. Table 11 ranked the causes of each tropical TMS defect; viz., weather, design, construction/installation process, aging, user involvement, cost pressures, workmanship, material selection, and fabrication techniques. The top four causes for the "fabrics may be tearing" defect are the weather (79.15%), material selection (50.00%), aging (50.00%), and materials (50.00%). The top three causes for "folding and scratches of the fabric" are: weather

(53.13%), material selection (41.67%), and aging (37.50%). Likewise, all the 18 types of TMS defects have their respective causes identified in Table 11. In general, weather is the top reason for all the TMS defects in tropics (a total score of 939), followed by aging (621), design (609), construction/installation (600), material selection (548), workmanship (427), fabrication techniques (331), user involvement (324), and cost pressures (322). There were seven countermeasures recommended by respondents and each scored from 1 to 5, including: a) use high quality materials; b) select workers that exhibit good behavior; c) schedule regular maintenance; d) increase TMS budgets; e) examine the design procedures and consider drainage, durability, and tensile stress; f) use proper construction/installation processes; and g) gain certification for TMS contractors (Table 12).

Table 11: Causes of TMS defects in the tropics

Type of Defects	Weather	Design	Construction/ installation process	Aging	User involvement	Cost pressure	Workmanship	Material selection	Fabrication techniques
Fabrics tear	76 (79.15%)	45 (46.88%)	32 (33.33%)	48 (50%)	12 (12.5%)	12 (12.5%)	29 (30.21%)	48 (50%)	25 (26.04%)
Folding & scratches of fabric	51 (53.13%)	31 (32.30%)	32 (33.33%)	36 (37.5%)	17 (17.71%)	20 (20.83%)	32 (33.33%)	40 (41.67%)	31 (32.30%)
Wrinkling of the fabrics	65 (67.71%)	36 (37.5%)	31 (32.30%)	40 (41.67%)	13 (13.54%)	18 (18.75%)	28 (29.17%)	32 (33.33%)	31 (32.30%)
Flapping and fluttering of the fabrics	51 (53.13%)	36 (37.5%)	36 (37.5%)	33 (34.38%)	15 (15.63%)	18 (18.75%)	28 (29.17%)	23 (23.96%)	29 (30.21%)
Degradation of fabrics	54 (56.25%)	31 (32.30%)	21 (21.88%)	43 (44.79%)	18 (18.75%)	19 (19.79%)	21 (21.88%)	37 (38.54%)	17 (17.71%)
Fungal decay, mould growth, and dirt in membrane	70 (72.92%)	23 (23.96%)	21 (21.88%)	33 (34.38%)	21 (21.88%)	11 (11.46%)	20 (20.83%)	28 (29.17%)	16 (16.67%)
Corrosion in anchor cables	61 (63.54%)	27 (28.13%)	29 (30.21%)	40 (41.67%)	18 (18.75%)	17 (17.71%)	13 (13.54%)	38 (39.58%)	16 (16.67%)
Deflection of anchor	36 (37.5%)	31 (32.30%)	23 (23.96%)	36 (37.5%)	24 (25.00%)	30 (31.25%)	22 (22.92%)	26 (27.08%)	27 (28.13%)
Slack or drooping cable/ropes	39 (40.63%)	34 (35.42%)	45 (46.88%)	23 (23.96%)	25 (26.04%)	14 (14.58%)	27 (28.13%)	25 (26.04%)	13 (13.54%)
Corrosion in cables	59 (61.46%)	30 (31.25%)	27 (28.13%)	39 (40.63%)	16 (16.67%)	17 (17.71%)	18 (18.75%)	34 (35.42%)	11 (11.46%)

Deflection of the mast	40 (41.67%)	35 (36.46%)	41 (42.71%)	35 (36.46%)	22 (22.92%)	24 (25.00%)	23 (23.96%)	26 (27.08%)	13 (13.54%)
Position changed of mast	44 (45.83%)	44 (45.83%)	59 (61.46%)	22 (22.92%)	6 (6.25%)	14 (14.58%)	18 (18.75%)	27 (28.13%)	10 (10.42%)
Corrosion of the rings and arches	70 (72.92%)	29 (30.21%)	30 (31.25%)	47 (48.96%)	6 (6.25%)	10 (10.42%)	16 (16.67%)	26 (27.08%)	7 (7.29%)
Corrosion or fatigue in fixings	54 (56.25%)	27 (28.13%)	31 (32.30%)	31 (32.30%)	20 (20.83%)	10 (10.42%)	23 (23.96%)	26 (27.08%)	14 (14.58%)
Cracks in foundation	35 (36.46%)	49 (51.04%)	47 (48.96%)	27 (28.13%)	15 (15.63%)	21 (21.88%)	30 (31.25%)	31 (32.30%)	15 (15.63%)
Deterioration of roof coatings	61 (63.54%)	39 (40.63%)	34 (35.42%)	33 (34.38%)	18 (18.75%)	17 (17.71%)	23 (23.96%)	36 (37.5%)	17 (17.71%)
Lighting breakdown	37 (38.54%)	31 (32.30%)	38 (39.58%)	19 (19.79%)	34 (35.42%)	20 (20.83%)	34 (35.42%)	19 (19.79%)	12 (12.5%)
Lack of water drainage and water pooling	36 (37.5%)	31 (32.30%)	23 (23.96%)	36 (37.50%)	24 (25.00%)	30 (31.25%)	22 (22.92%)	26 (27.08%)	27 (28.13%)
Total	**939**	**609**	**600**	**621**	**324**	**322**	**427**	**548**	**331**

Table 12: Countermeasures of TMS defects in the tropics

No.	The key factors to increase the feature TMS	Score
1	Use high quality material	5
2	Choose workmanship with good behavior	4
3	Scheduled maintenance	4
4	Increase TMS budget	3
5	Examine the design procedure considering drainage, durability, and tensile stress	2
6	Use proper construction/installation process	2
7	Certification for TMS contractors	2

Critical Discussion about these Findings

The "deterioration of roof coatings", "corrosion or fatigue in fixings", "fungal decay, mould growth, and dirt in membrane", "corrosion in anchor cables", and "degradation of fabrics" are the five most frequently occurring TMS defects in the tropics. The deterioration of roof coatings is largely caused by the strong ultraviolet radiation in this region. The coating is vital for TMS durability as it contributes to the strength of the fabrics and it protects both the fabrics and the membrane. Shaeffer (2000) ranked the deterioration of roof coatings as only the fourth most frequent defect in his study, and ignored the possible impact of climatic and regional effects. However, in our research, "deterioration of roof coatings" is shown as the most common defect because of the strong solar radiation and intense precipitation; both of which are stronger in the tropics than in other climate zones. This proposition was partially supported when we sought to identify the causes of TMS defects, which indicated that "weather" was regarded as the most significant cause. The maintenance work required for TMS does not need to be frequent and usually no consideration is given to changing the coating, leading to no change over life of the structure even when deterioration occurs. We identified "corrosion or fatigue in fixings" as the second most frequent TMS defect in the tropics due to the poor corrosion protection and weather, this is supported by Macdonald's (2001) assertion that corrosion or fatigue in fixings always occurs in large TMS structures. Further, "fungal decay, mould growth, and dirt in membrane" was identified as the third most frequent defect and the reason may be alluded to in Shaeffer's (2000)'s study which identified that moisture levels and poor maintenance are crucial in TMS construction and use, but which we rank as much more significant, overall. The other kinds of corrosion defects occurring in TMS (e.g., corrosion in anchor cables, rings, arches, and ropes) are primarily due to poor corrosion protection (Foster et al., 2007). Most TMS fabrics in this study were covered by PVC, silicone, or PTFE. The fifth most common TMS defect in the tropics is "degradation of fabrics"; this is strongly correlated with the defect "fungal decay, mould growth, and dirt in membrabe", which is logical as when the fabric degrades, the microbes and fungus can more readily impregnate the material.

Conclusions and Recommendations

While TMS has been applied in the tropics with great success, its defects relative the specific climatic and weather conditions of the region have never been specifically examined. This study identified the most frequently TMS defects in the tropics as "deterioration of roof coatings", "corrosion or fatigue in fixings", "fungal decay, mould growth, and dirt in membrane", "corrosion in anchor cables", and "degradation of fabrics". The relative ranking of these defects is quite different from that found in other climatic zones. The top five causes of TMS defects in the tropics are the weather, aging, design, construction/installation, and material selection. Weather is a primary cause of TMS defects in the tropics more so than in other regions; the UV rays and precipitation place greater strain on the TMS materials. We found that only "corrosion or fatigue in fixings" is a significant predictor for "deterioration of roof coatings"; while this is not a causal effect, it does indicate that TMS maintenance staff do not have to climb up to the roof to check the deterioration of coatings but can instead predict failure by measuring the corrosion of the fixings. There were seven countermeasures recommended: a) using high quality materials; b) selecting workers exhibiting good behaviors; c) scheduling regular maintenance; d) increasing the budget for TMS builds; e) examining the design procedures and considering drainage, durability, and tensile stress; f) using proper construction/installation processes; and, g) implementing a certification programme for TMS contractors. However, these countermeasures have not been analyzed in this study and further research should examine their use in a long-term, longitudinal research design. The countermeasures may need to be tested in new TMS projects and some require policy support. This highlights the importance of future case study research examining TMS defects.

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