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THE FOURTH CHIAM TEONG TEE MEMORIAL LECTURE

*Presented at New World Hotel Petaling Jaya,
Selangor Darul Ehsan, Malaysia
on 6th November 2021*



Ir. Er. Dr C.T. Tam
Honorary Fellow
Department of Civil & Environmental Engineering,
National University of Singapore

Ir. Er. Dr Tam has been involved with the study of concrete and its constituent materials for over 50 years after graduating in Civil Engineering in 1958. He began his academic career in 1963 at the Department of Civil Engineering of University of Malaya and since 1979, at the Department of Civil & Environmental Engineering, of National University of Singapore. Throughout this period, the transfer of findings and practices from the more established countries in temperate climatic regions to meet the required performance in tropical climate has provided the motivation and challenges in research and engineering practice.

Recognizing that the difference in ambient temperature between the two regions is a significant factor requiring consideration in the performance of concrete, the need to develop modifications to achieve similar performance and to introduce them through local standards and site practice has been his on-going career activities. An example is the introduction of layered casting method for thick raft

foundations to minimize potential DEF and early thermal cracking in tropical climate.

Ir. Dr Tam obtained BE (Hons) and ME from the University of Adelaide, South Australia and PhD from the University of Calgary, Canada. He is a registered P.Eng. in both Malaysia and Singapore, C.Eng. in UK, FIEM, FIES, FIStructE, FACI, FCS and member of Technical Committees in ASTM, ACI and Enterprise Singapore for over 40 years, and the transition to Eurocodes in Singapore since 1 April, 2013. Past President of Singapore Concrete Institute, First Life Member (1997), and Life Time Achievement Award, (2009), Past President of ACI Singapore Chapter, and Distinguish Chapter Member (1999). Recipient of Gold Medal, SISIR, (1985), Distinguish Award, SAC, (2006), Distinguish Partner Award, SINGLAS, (2010), Special Recognition of Partners, (2016) SPRING, and CSM Excellent Award, Concrete Society of Malaysia, (2008). Effective from 1 July 2019 Ir. Dr Tam received Honorary Fellow appointment at NUS.

4TH CHIAM TEONG TEE MEMORIAL LECTURE

THE PAST, PRESENT & FUTURE OF CONCRETE CONSTRUCTION

(Date received: 26.01.2022/Date accepted: 28.02.2022)

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ABSTRACT

Concrete has always been the major construction material since the historical past, at present and will continue into the future. This presentation covers the period from the first UK design code (CP 114, 1957) in UK to the current European design code (BS EN 1992-1-1: 2004) and their associated standards on concrete and its constituent materials. The 10th Professor Chin Fung Kee Memorial Lecture in 2000 on "Concrete: From 2000 psi to 80 MPa and Beyond" was delivered before the adoption of Eurocodes. This new system is based on performance approach, in place of the more prescriptive approach of the former UK system. Engineering education and practice have to meet the changes with updated knowledge to benefit from these advances in design, materials and construction. The main emphasis is on changes in concrete with new types of cement, addition, admixture and the diminishing stock of aggregates. Replacing the traditional reliance on past experience with innovative approaches in concrete technology based on acceptance of rational performance criteria leads to progress in the construction industry. The progressive advances over the past six decades provided by personal experience have transferred through the teaching, research and development of new concrete concepts in concrete technology to the construction industry. There is also an urgent need to look into the future direction for concrete and the associated challenges ahead with the expected global warming to achieve higher levels of strength, consistence and durability for a sustainable concrete construction industry.

Keywords: *Concrete, cementitious materials, additions, admixtures, strength, consistence, durability, sustainability*

1.0 INTRODUCTION

Concrete has always been the major construction material since the historical past, at present and will continue into the future. This presentation covers, the period from the first UK design code (CP 114, 1948, revised 1957) in UK to the current European design code (BS EN 1992, 2004) and their associated standards on concrete and its constituent materials. The 10th Professor Chin Fung Kee Memorial Lecture (Tam, 2000) on "Concrete: From 3000 psi to 80 MPa and Beyond" was delivered before the adoption of Eurocodes. This new system is based on performance approach, in place of the more prescriptive approach of the former UK system.

2.0 CONSTITUENT MATERIALS FOR CONCRETE

2.1 Cement

Concrete is a composite material consisting of cement, water and both fine and coarse aggregates in appropriate compositions to achieve adequate strength for structural safety, sufficient

consistence (formerly workability) for ease of construction, and durability of a chosen intended design working life in its exposure environment during service.

The term cement as defined in BS EN 197-1 (2011) refers to 27 types of common cements and 7 types of sulfate resisting common cements. Formerly BS 12 (1978) had 2 types of Portland cements, (a) Ordinary Portland Cement, (OPC) and (b) Rapid Hardening Portland Cement, (RHPC). As most concrete construction projects preferred RHPC over OPC for faster rate of strength development, OPC become "Obsolete" Portland cement and was left out in the revised BS 12 (1991). Even though it is no longer produced, the term OPC remains in common use in specifications and publications.

With the change from individual specification for each type of Portland cements in UK to all types under a single standard (EN 197-1), designers and specifiers have to select and specify which of the 34 types is to be used for a specific application. Each type of common cement has its advantages and disadvantages in terms of both technical and cost implications. Engineering education and practice have to meet the changes with updated knowledge to make the most appropriate selection with understanding of the physical and chemical compositions of each type of cement. In

addition, the use of additions and chemical admixtures and their effects on both fresh and hardened properties of concrete are important factors in the final specification of concrete for each specific application.

The role of supplementary cementitious materials (SCM/ additions) such as fly ash (FA), ground granulated blastfurnace slag (GGBS) and silica fume (SF) in relation to pozzolanic reactions needs to be appreciated. The secondary reaction becomes significant when the primary reaction of the cement (CEM I) with water has generated sufficient calcium hydroxide to activate the silicates in the SCM either as a blended cement (EN 197-1) or batched into the mixer, defined as combination in BS 8500-1 (2016). The SCMs are deemed to be by-products and hence of a much lower carbon footprint compared to cement clinker to achieve better sustainability for concrete.

The drive to lower carbon footprint in cement has led to the development of non-Portland cements, e.g. geopolymers. In UK a newly published document, Publicly Available Standard, PAS 8820 (2016) applies to all types of alkali-activated cementitious materials. Some examples of application of this new type of cement have been reported by Ball and Greet (2014) and Aldred *et al* (2015).

2.2 Water

Water is other necessary component in concrete. In urban centres potable water is suitable and available for use as both mixing and curing water for concrete. Where potable water is not available, there is a need for acceptance criteria and test methods to be adopted to ensure the water is suitable as mixing and curing of concrete. The former BS 3148 (1980) was useful as a guide but did not provide acceptance criteria. Currently BS EN 1008 (2002) is a specification for mixing water stating both test methods and conformity requirements. It includes the use water recovered from processes in the concrete industry, as mixing water for concrete to promote conservation of resources as well as avoidance of treatment before disposal.

2.3 Aggregates

Aggregates form the largest volume of constituents in concrete as a composite material. The combined grading of fine and coarse aggregates serves to form the particles in the matrix of cement paste (two phase concept). There are only limited changes compared to the former BS 882 (1992). The major difference is that BS 882 (1992) was limited to “aggregates from natural sources for concrete”. A minor change is in the maximum particle size for fine aggregate. BS EN 12620 (2010) changed the upper size of fine aggregate from 5 mm sieve to 4 mm sieve size. In the 1973 edition of BS 882 four grading zones were introduced. “The division into zones was based primarily on the percentage passing the 600 µm (No. 30 ASTM sieve) sieve. The main reason for this was that a large number of natural sands divide themselves at just that size, the gradings above and below being approximately uniform” (Neville, 2012). This was based on sands available in UK. “Little of these sands is now available for concrete-making, and a much less restrictive approach to grading is reflected in the requirements of BS 882: 1992” (Neville, 2012). Only an overall grading is required with three additional grading limits into coarse, medium and fine grading with overlapping ranges. Similar approach is adopted in BS EN 12620 (2002) Annex B (informative). Coarseness or fineness is based either

on the percentage passing the 0.500 mm sieve (replacing former 0.600 mm sieve) or on the fineness modulus (adopted also by ASTM C33-18). Fineness modulus (FM) is calculated as the sum of cumulative percentages by mass retained on the following sieve (mm) expressed as a percentage, i.e.

$$FM = \sum\{(>4) + (>2) + (>1) + (>0.5) + (>0.25) + (>0.125)\}/100$$

Comparison of the former BS 882 and current BS EN 12620 and ASTM C33-18, on the coarseness or fineness requirements as shown below:

BS 882: 1992 - Percentage by mass passing sieve

Sieve size	Coarse	Medium	Fine
2.36 mm	60-100	65-100	80-100
1.18 mm	30-90	45-100	70-100
600 µm	15-54	25-80	55-100
300 µm	5-40	5-48	5-70

BS EN 12620: (2002) – Percentage passing 0.500 mm sieve

CP	MP	FP
5-45	30-70	55-100

BS EN 12620: (2002) – Fineness modulus

CF	MF	FF
4.0-2.4	2.8-1.5	2.1-0.6

ASTM C33-38 – FM: 2.3-3.1

It can be observed that a wide range of fine aggregate grading as indicated above can be used in concrete. Hence, actual usage can be developed by “initial tests” to meet specified performance often at an increased cost rather than technical limitations.

BS EN 12620 (2002) includes the use of recycled aggregates (RA) and recycled concrete aggregates (RCA). BS 8500-1 (2016) introduced separate definitions for RA from reprocessing of inorganic material previously used in construction and crushed concrete aggregate (CCA in place of RCA) which is principally comprising “aggregate obtained from crushed concrete”. “Coarse CCA and coarse RA conforming to BS 8500-2 may be used in designed concrete up a maximum strength class C40/50”. “Coarse CCA obtained by crushing hardened concrete of known composition that has not been in use and not contaminated during storage and processing may be used in any in any strength class”. Such concrete elements may be from concrete test specimens for production conformity and precast elements that are rejected for production imperfection. “Although provisions for the use of fine CCA and fine RA are not given in BS 8500, this does not preclude their use where it is demonstrated that, due to the source of material significant quantities of deleterious materials are not present and their use has been specified or permitted”, e.g. permitted by project specification under “provisions valid in the place of use”. The new standard promotes the drive for sustainable concrete construction further considered in the section 5.5 on Sustainability.

2.4 Additions and Admixtures

The term addition in common usage often includes both mineral additions and chemical additions. BS EN 206 (2016)

separates the two by their functions in concrete. Addition is used in concrete “to improve certain properties or to achieve special properties”, e.g. Pozzolanic or latent hydraulic additions such as fly ash, ground granulated blastfurnace slag and silica fume. Admixture is used in concrete “to modify the properties of fresh and hardened concrete”, e.g. plasticizing and retarding/accelerating set.

2.4.1 Additions

The most commonly used additions in concrete production are fly ash, ground granulated blastfurnace slag and silica. Fly ash is the by-product from the burning of pulverized coal. Fly ash for concrete is to be in accordance with BS EN 450-1 (2012), Fly ash for concrete – Part 1: Definition, specifications and conformity criteria. Ground granulated blastfurnace slag for use in concrete is to be in accordance with BS EN 15167-1 (2006), Ground granulated blastfurnace slag for use in concrete, mortar and grout – Part 1: Definitions, specifications and conformity criteria. Silica fume for concrete is to be in accordance with BS EN 13261-1 (2009), Silica fume for concrete – Part 1: Definitions, specifications and conformity criteria.

Use of additions in accordance with BS EN 206 (2016) has to meet conditions set in Annex A (normative) for “initial test”. Suitability is established by any one of the concepts in Clause 5.2.5, “the k-value concept in 5.2.5.2.2 and the principles of the equivalent performance concepts (equivalent concrete performance concept (ECPC) in 5.2.5.2.3, and equivalent performance of combinations concept (EPCC) in 5.2.5.2.4. Further details on this topic are presented in a later section on concrete (3.4 Durability).

2.4.2 Admixtures

The earliest application of admixtures is air-entraining agents to meet freeze-thaw exposure which is not normally considered in tropical climate. In the 1960s, water-reducing and set-retarding admixture (1st generation, 1G) was lignosulfonates derived from leaching process in paper manufacture with reduced wood sugar. Superplasticizers in the 1980s are mainly naphthylene-formaldehyde-based (NSF type, 2G) specially produced in chemical plant. By the 1990s, polycarboxylate with long EO chains (PE type, 3G) is added. Since 2000s, PCE type (4G) provides engineered performance with enhancement of retardation or plasticizing functions. For PCE type, the absorption unit (carboxyl group in the main chain) and the steric repulsion unit (EO polymer in the side chain) can be independently engineered to vary the extent of set-retardation or the plasticizing function. Three types of applications are commonly available with superplasticizing admixture: (1) addition of plasticizer to increase consistence without change in strength, (2) reducing water content without change in consistence and at the same cement content to increase strength and (3) reduction is both water content and cement content but retaining the same water/cement ratio for strength and same consistence, resulting in cost saving for the same performance. Conformity testing of admixtures is in accordance with BS EN 934-2: 2001+A1:2012, Admixtures for concrete, mortar and grout – Part 2: Concrete admixtures – Definitions, requirements, conformity, marking and labelling, based on equal water/cement ratio, equal consistence and equal water/cement ratio with prescribed concretes.

With each new generation of set-retarding and plasticizing admixtures for a given water/cement ratio for strength, the required level of consistence is achieved with lower water content and hence also a lower cement content. Besides a saving in cost, there is the added reduction in embedded CO₂/m³ of concrete. In recent years, further functions are introduced into chemical admixtures, e.g. shrinkage compensating (drying shrinkage) or shrinkage reducing (autogeneous shrinkage) and a move to introduce corrosion resistance function to the next generation of standardized chemical admixture. Former chemical admixture standard BS 5075 Parts 1 to 3 are replaced by BS EN 934 Parts 1 to 6 Admixtures for concrete, mortar and grout which cover definitions, requirements, conformity, marking and labeling for admixtures, including grout for prestressing tendons and sprayed concrete.

2.5 Fibres

Two types of fibres are permitted in BS EN 206 (2016). These are steel fibres conforming to BS EN 14889-1 (2016) and polymer fibres conforming to BS EN 14889-2 (2016). Fibre content and homogeneity test methods and acceptance criteria for identity test are specified in Annex B (normative) of BS EN 206 (2016).

Polymer fibres have been used to mitigate plastic shrinkage cracking and steel fibres to replace conventional reinforcement gage in tunnel segment. Combination of these two types of fibres is becoming more common to achieve special performance, including fire rating besides crack control. Non-metallic fibre-reinforced polymer is a composite material made of a polymer matrix reinforced with fibres. “The fibres are usually glass (in fiberglass), carbon (in carbon fiber reinforced polymer), aramid, or basalt” (Wikipedia – Fibre-reinforced plastic, 08-Oct-19). Glass fibre reinforcement bars used in a foundation of a medical centre in France also meets the need to be electromagnetic interference-free (Revans, 2019).

3.0 CONCRETE

3.1 Historical Practice

Both in UK and USA, codified design and specification for concrete began around the mid-1930s. Over the next 8 decades, British codes for concrete evolved from the DSIR Code of 1934 to CP 114 (1948, revised in 1957) to CP 110 (1972) and the BS 8110: Part 1 (1985). This is currently replaced by BS EN 1992-1-1 (2004) and BS EN 206 (2016). Guidance on specification of concrete including durability first appeared in CP 110 (1972) as BS 5328 (1976) and expanded into 4 Parts in 1990 and 1991. Currently BS EN 206 (2016) has complementary UK standards (BS 8500-1 and 8500-2: 2016) for additional guidance. Similar complementary national standards based on UK guidance documents are published for guidance in Malaysia and Singapore. Only the specification of concrete will be presented in this lecture. The topics are compressive strength, consistence and durability.

3.2 Compressive Strength

Compressive strength of concrete can be correlated to other types of concrete strength and is the strength used in design.

In CP 114 (1957) it was based on nominal concrete mixes, e.g. 1:2:4 consisting of 112 lb of cement (= 50 kg bag), 2.5 cubic foot of fine aggregate and 5 cubic foot of coarse aggregate. The 28-day cube strength was to be 4000 psi (28 MPa) for preliminary test (trial mix/initial test) and 3000 psi (21 MPa) for works test (site samples). The working stress of concrete (in compression) of 1:2:4 concrete was 760 psi (5.3 MPa) in direct compression and 1000 psi (7 MPa) in bending based on elastic theory. The concept of characteristic strength was introduced in CP 110 (1972) with the change over from elastic design to limit state design with partial safety factor for load and for strength. The highest grade of strength is 60 MPa and remained the same in BS 8110 (1985). However, the modulus of elasticity was higher in CP 110 (1972) than in BS 8110 (1985), e.g. at the characteristic strength of 60 MPa, the static elastic modulus CP 110 (1972) was 36 GPa (mean) in the range of 30 to 42 GPa compared to the lower values in BS 8110 (1985) of 32 GPa (mean) in the range of 26 to 38 GPa. It is to be noted that in BS EN 1992-1-1 (2004) for the same characteristic strength of 60 MPa, the value is 37 GPa. The highest characteristic compressive strength in BS EN 1992-1-1 (2004) is C90/105 for which the elastic modulus is 44 GPa. It is a challenge to source for high strength coarse aggregate to achieve such high elastic modulus.

The design of concrete structures in BS EN 1992-1-1 (2004) adopts standard cylinder strength, but conformity may be based on either cylinder or cube compressive strength as stated in BS EN 206 (2016). For strength classes up to C55/67, standard (150 mm) cube compressive is around 1.25 times of standard (150 mm diameter by 300 mm length) cylinder compressive strength. From C60/75 to C100/115, a constant difference of 15 MPa is adopted. There is adequate experience and track record in the use of concrete strength class up to C55/67 but much less above it, it is prudent to test both type of standard specimens in the "initial test" stage (trial mix in current practice) to gain more confidence in the relationship, particular for countries where cube compressive strength is adopted for conformity. There is also the need to do the same as strength classes above C100/115 is expected in the future. The use of concrete with a higher strength class leads to smaller dimensions of structural elements which may lead to saving in cost but more so in materials for sustainability in concrete construction. Whether there is a reduction in carbon footprint will depend on the balance between the need of an increase in cement content for higher strength concrete versus the reduction in its volume to achieve the same structural requirements. Other benefits include less labour and time in casting and handling of concrete in production and transportation from plant to site. Possible cost saving in formwork and faster time for completion of project are added advantages.

In terms of reduction in concrete volume and hence cement used to achieve the objective of sustainability, the use of 100 mm cubes in lieu of 150 mm cubes for conformity testing should be promoted. The volume of concrete for one 150 mm cube (0.003375 m³) is sufficient to make three 100 mm cube (0.001 m³) with spare. The current practice of specifying standard cube strength to be determined with 150 mm cubes is likely due to the convenience of using one size to include concrete with 40 mm maximum aggregate size (e.g. pavement and unreinforced

mass concrete applications). In most concrete construction, maximum aggregate size of 20 mm is specified and even 10 mm in cases of higher strength classes. The relation between specimen size and maximum aggregate size specified in BS 1881 (1952) prescribed a test cube not smaller than 4 in. (100 mm) when ¾ in. (20 mm) aggregate is used and 6 in. (150 mm) cubes with 1½ (40 mm) aggregates. ASTM C192 (1957) limits the ratio of the diameter of the cylinder to the maximum aggregate size to 3. "A value of between 3 and 4 is generally accepted as satisfactory" (Neville, 2012). According to BS EN 12504-1 (2000) the ratio of maximum aggregate size in the concrete to the diameter of the core has a significant influence on the measured strength, when it approaches a value greater than about 1:3. BS 8500-2 (2016) under conformity control for compressive strength it requires conformity to specified compressive strength class when determined using 100 mm cubes, "the minimum characteristic 100 mm cube strength shall be that prescribed for 150 mm cubes in BS 206 (2016)". The acceptance of 100 mm cubes for conformity has been in UK practice for many decades based on BS 1881 (1952). The relationship between compressive strength and water-cement ratio used in designed concrete given in Road Note No. 4 (1950) is based on 100 mm (4 in.) cubes. This is the basis which subsequent design of concrete methods adopt as the guide for selecting water-cement ratio for a given compressive strength.

According to size effect, smaller dimension specimens are expected to show higher measured strength. Neville (2012) reported limited published data in terms of cube compressive strength indicate the ratio of 100 mm (4 in.) cubes to that of 150 mm (6 in.) cubes at about 1.04. Smaller size specimens also tend to result in higher variability in terms of standard deviation or coefficient of variation. However, the combined effect on characteristic strength is reduced. The value of the ratio = 1.05 was reported by Leung & Ho (1996) based on 8 projects with values of below 1.0 range from 4% to 22% with the mean for 17% for 349 individual ratios. Most of studies are limited in the size of the population for each strength level with each data based on the average of 3 specimens at each test age. Limited number of test data is unlikely to follow assumption of Gaussian distribution. Hence for small sample size the tendency is to have more results above the mean. The cube/cylinder strength ratio for concrete tends to be above unity. Daneti *et al* (2016) conducted a study with three strength levels (C32/40, C50/60 and C65/80) over a period of several months in a RMC plant used in actual production. A total of slightly over 100 batches for each strength level were produced and tested at the age of 28 days with moist curing from time of demoulding at age of one day. In all cases, the mean value of the ratio between 100 mm and 150 mm cubes is only 1.01 based on mean of individual batches or characteristic value. The average value for standard deviation of each cube size differs by less than 0.05 MPa. The distribution of the ratio for each of the 3 strength levels shows skew towards values above 1.0 with the percentage of value below 1.0 at 31% for C32/40 and C50/60 and even lower at 21% for C65/80. Based on this observation, it implies that for small number of batches, there is a high probability that the ratio will be above 1.0 as reported in other studies. It also supports the recommendation of BS 8500-1 (2016) to accept conformity based on the same as prescribed for 150 mm cubes in BS EN 206 (2016).

3.3 Consistence

Consistence is the new term for workability. Care should be taken to differentiate its usage from "consistency" which is the quality of always behaving or performing in a similar way. **As an example: quality assurance relies on the *consistency* of a concrete produced with the required *consistence* (e.g. slump) over the period of production.**

Normally, consistence in BS EN 206 (2004) may be specified in terms of different slump classes (S1 to S5, BS EN 12350-2:2009), compaction classes (C0 to C4, BS EN 12350-4:2009) and flow classes (F1 to F6, BS EN 12359-5 2009). Slump flow classes (SF1 to SF3, BS EN 12350-8 2010) apply to self-compacting (self-consolidating) concrete only. Although the final flow diameter and slump flow diameter are determined in both methods, "flow, F" and "slump flow, SF" are based on different test standards (cone size etc.). There is no direct correlation between consistence classes of one test method with those of another test method.

For SCC there are additional requirements. They include viscosity classes (VS1 and VS2 to BS EN 12350-8 2010) based on t_{500} , the time for flow to reach 500 mm in slump flow test and/or (VF1 and VF2 to BS EN 1250-9 2010) based on t_v , the time for flow through the V-funnel. The passing ability classes (PL1 and PL2 to BS EN 1259-10 2010) using the L-box and/or (PJ1 and PJ2 to BS EN 12350-12 2010) using the J-ring. In addition there is the sieve-segregation resistance classes (SR1 and SR2 to BS EN 12350-11 2010). The above types and ranges of consistence classes have been developed for specification needs. This is a great advancement from the requirement in CP114 for a given water/cement ratio: "The quantity of water used for reinforced concrete should be sufficient, but not more than sufficient, to produce a dense concrete of adequate workability for its purpose, which will surround and properly grip all the reinforcement. So far as possible, the workability of the concrete should be controlled by maintaining a water-cement ratio that is found to give a concrete which is just sufficiently wet to be placed and compacted without difficulty, with the means available". One should note that in those days, placing and compacting concrete were undertaken mostly by ladies known commonly as "Sam Sui Women" with reference to their home village in China. The women wearing typical red colour hair covering had only round reinforcement rods for compacting concrete. Yet with their dedication and passing to do things right, many structures built in those days are still standing. This is a far cry from to-day where SCC is used with no human effort needed for obtaining adequate compaction. Robots can now replace human in casting concrete within a factory for precast products! On the other hand, very low consistence concrete is needed for 3D printing method of constructing concrete structures. In Europe, some very interesting buildings and even a pedestrian bridge have been created with 3D printing techniques. Locally, an experimental prefabricated volumetric bathroom unit has been produced by this new technique in Singapore.

3.4 Durability

For this lecture only the provisions on exposure classes and requirements for composition of concrete are considered as they are developed over the past decades in specification requirements. Information on mechanisms and rate of attack, etc are available in many published documents and textbooks on concrete.

The durability exposure classes are generally given in a descriptive form. Similarly, requirements on concrete constituents and composition are also prescribed in descriptive terms. In CP 114 (1957) clause 210 highlighted the need for specified cover for reinforcement bars and concrete "should be dense, impermeable and of a quality suitable for the conditions of exposure involved". No specific details were provided, other than "nominal concrete mixers should not be used for structures exposed to sea water". Clause 352 covered the resistance to chemical attack mentioned chemical agents "such as vegetable oils and fats, sugar solutions and sulphates". "Increased resistance to some forms of chemical attack may be obtained by the use of high alumina cement or sulphate resisting cement or by the use of protective coatings".

CP 110 (1972) provided specific guidance on "minimum cement content" in Table 48 in which exposure were classified as "mild", "moderate", "severe" and "subject to salt for de-icing", with "the cement content should be sufficient to provide adequate workability with a low water/cement ratio so that the concrete can be completely compacted with the means available". Limits on maximum free water/cement ratio and minimum grade of concrete were introduced in BS 8110 (1985) for durability with also two new exposure conditions, "very severe" and "extreme". Details were provided in the new BS 5328 (1990-1991, in 4 parts). The current UK guidance is provided in Annex A (informative) of BS 8500-1: 2015+A1 (2016). Exposure classes and requirements on concrete includes types of cement and concrete cover in addition to minimum cement content and maximum free water/cement ratio as in previous UK standards. The provisions are in more details and included both intended design working life of 50 years and 100 years. Hence, they are preferred to the k-factor approach in clause 5.2.5.2 of BS EN 206 (2013) for intended design working life of 50 years covering only for fly ash and silica fume, but as informative value for ground granulated blastfurnace slag. The relevant standards provide full details for inclusion in specifications.

For sulfate in the ground, CP 110 indicated classes 1 to 5 based on concentration of sulfates with the requirements for minimum cement content and maximum free water/cement ratio. BS 5328 (1990-1991) refined class 4 into 4A and 4B and class 5 into 5A and 5B based on BRE Digest 363 (1991) which has been replaced with BRE Special Digest 1, 3rd Ed. (2005) Concrete in aggressive ground. The current UK guidance is provided in Annex A (informative) of BS 8500-1: 2015+A1 (2016) which provides much more guidance than the recommendations in Annex F (informative) of BS EN 206 (2013). In both Malaysia and Singapore, the UK approach in provisions for durability has been adopted historically from the colonial days. Even though the approach is semi-prescriptive, past performance and familiarity with the practice have served the needs adequately and should be followed until truly performance based design methods currently under development are codified. The two cases of carbonation in concrete and the diffusion coefficient for chloride ingress are likely to be the first to be introduced when the effects of various factors of the numerical equations are agreed upon. These include the service exposure environment factors such as temperature and relative humidity and factors in the resistance provided by concrete such as cement type and content, water/cement ratio and nominal design cover to reinforcement. All the factors will be in quantitative terms to replace of the

current descriptive approach and semi-empirical prescribed values for concrete. In order to validate the recommended values for various factors, actual site exposure performance data are necessary to correlate them. It is in this regard that monitoring of existing concrete structures is very much limited in tropical climate. A few studies under controlled exposure in laboratory studies have been published. However, actual performance under service environment has not been monitored, particularly with adequate information on the insitu quality of the concrete cover and continuous recorded environmental data in tropical climate. This is an urgent issue as data from temperate climate will not adequately represent tropical climate. In the Foreword to the complimentary Singapore standard SS 544 (2019), guidance to cater for the higher tropical temperature when using recommended requirements for concrete in BS 8500 (2016) it is recommended to enhance the resistance of concrete. "In order to cater to the higher ambient temperatures in Singapore compared to UK, the recommendation is to consider the required concrete for at least one class higher than that based on exposure conditions in accordance with the requirements for UK exposure conditions (refer to Table A.3). The specifier should take into consideration the nature of the element, intended working life, its importance and the cost of maintenance and repair to select the same or higher performance concrete". Different elements in the same structure may be specified with different concrete to optimize cost-effectiveness. Limited data on the effect of tropical temperature over that in temperate regions have indicated significantly higher rate of carbonation and lower service life in marine exposure conditions (Otsuki *et al* 2006).

The above applied to chemical attack by sulfate from an external source which results in spalling from the surface in contact with the external source, e.g. soil or seawater. However, another type of sulfate attack comes from sulfate already within the concrete. This is referred to as internal sulfate attack (ISA) or by the delayed reaction product between sulfate (calcium sulfate sources, such as gypsum, intentionally added to Portland cement to regulate early hydration reactions to prevent flash setting, improve strength development, and reduce drying shrinkage) and the tricalcium aluminate in Portland cements to form ettringite (calcium sulfoaluminate ($3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot 3\text{CaSO}_4\cdot 32\text{H}_2\text{O}$)). Ettringite formed at early ages is often referred to as "primary ettringite." It is a necessary and beneficial component of Portland cement systems. Delayed ettringite formation (DEF) results in expansion and cracking of concrete associated with the delayed formation of ettringite which is a normal product of early cement hydration. This reaction ends when the sulfate concentration, needed for forming the ettringite, decreases below the limit. From this point the remaining C3A reacts with the already formed ettringite to monosulfate which in aqueous solution again form ettringite and tetracalcium aluminate hydrate. DEF is a result of high early temperatures (above 70°C – 80°C) in the concrete due to heat of hydration of cement which prevents the normal formation of ettringite, e.g. in thick sections. The occurrence of this form of sulfate attack in concrete was not fully recognized until late 1990's. It attracted much attention when accelerated curing of precast pretensioned railway sleeper in Europe showed map cracking after in service for several years. In those days, the accelerated curing regime had upper temperature maintained at 80°C for several hours. Since the phenomenon was recognized, the upper temperature is now kept at 60°C

(possibly to avoid potential local hot spots within the curing environment). Up till the late 1990's some thick raft foundations and large pilecaps would have exceeded 70°C for which DEF may have occurred during service. The highest temperature found in published literature was over 90°C , incidentally shown in the publication by Cao (2000) on the construction of Jin Mao building. However, in such cases, it is likely that the volume of affected concrete is small and limited to the central core portion of the mass. Under compressive loading of the superstructure and the confinement effect of reinforcement cage in reinforced concrete, the resultant expansion due to DEF may not lead to any observed surface cracking during service.

In temperate regions, typical summer temperatures are around 20°C and down to around 10°C or lower in winter. For initial placing temperatures in these temperatures, maximum temperature developed in thick sections seldom exceeds 70°C . Hence, the main concern is potential early thermal cracking. Nominal guidance on potential early thermal cracking suggests the temperature differential between the warmer interior and the cooler surface zone should be below 20°C , e.g. BS 8110-2 (1985). For tropical climate average ambient temperature throughout the year is around 28°C to 32°C . Keeping maximum concrete temperature below 70°C is possible at a high cost (either by means of pre-cooling of fresh concrete or by post-cooling of hardened concrete). Studies over the past two decades reported by Godart and Divet (2017) that cements containing SCM's meeting certain limits may have acceptable expansion without cracking due to potential DEF for peak hydration temperatures up to 75°C , 80°C or 85°C .

Guidance on potential early thermal cracking given in BS 8110-2 (1985) Table 3.2 Estimated limiting temperature differential to avoid cracking is related to the statement: "Experience has shown that by limiting temperature differentials to 20°C in gravel aggregate concrete, cracking can be avoided. This represents an equivalent restraint factor R of 0.36 and the corresponding values for concrete with other aggregate types are given in table 3.2". The limiting value at the same $R = 0.36$ for granite aggregate concrete is 27.7°C and for limestone aggregate concrete 39.0°C . Values of external restraint recorded in various structures given in Table 3.3 indicate for mass pour cast on blinding, e.g. raft foundation, R is 0.1 to 0.2, but for thin wall cast on to massive concrete base, R is 0.6 to 0.8 at base and 0.1 to 0.2 at top. Local experience has indicated that for raft foundations temperature differential up to 30°C to 35°C in raft foundations but a value of 12°C to 14°C has resulted in through cracks in thin walls cast on to massive concrete base due to high base restraint. Mitigating methods need to be developed to minimize this latter case in cut-and cover tunnel walls and tank walls for liquid containing tanks. Reducing boundary restraint is the mitigating approach, e.g. a low first lift with both ends free.

It is a common practice to rely on numerical analysis based on heat of hydration data from a "hot box" test to assess both issues. However this approach does not include the casting process which may take up over 10 hours or more in raft foundations. During this time, concrete placed earlier has already started to rise in temperature. Numerical analysis to include this stage is complicated by the need to change the thickness of concrete with time. In order to cater for this, a realistic mock-up method has been developed (Tam *et al*, 1997). It enables innovative concepts to be adopted when casting fresh concrete in multiple horizontal

layers to ensure proper compaction, reducing cost by introducing the "ice-cream sandwich concept". Cost saving is achieved with only the interior zone with cooler concrete but both bottom and top outer zones with normal initial fresh concrete temperature. The concretes for different layers are designed for the same compressive strength but with optimization of the concrete designed not only of different initial placing temperatures but also include different types of cements and chemical admixtures of different functions (e.g. waterproofing, besides plasticizing and set-retarding). Using this approach, more than 2 million cubic metres of concrete for raft foundations have been satisfactorily placed over the past two decades in both Malaysia and Singapore. Similar concept of casting realistic simulation with a mockup has also been applied to casting of thick transfer girders, transfer plates and large diameter columns with high strength concrete of C60/75 and above.

For the case of thin wall cast on to massive base, the base restraint factor has been satisfactory reduced by casting the first lift of the wall with not exceeding 1 m. Preferably both ends of the wall are free or only one end of the wall may be continuous with existing wall of the same thickness but keeping the other end free. Limited local experience has shown that the free contraction of the top together with free end(s) of the new to be cast section of the wall is able to reduce the restraint factor sufficiently to avoid cracks being developed.

3.5 Sustainability

Constituents for concrete are increasing in demand for economic development in both developed and developing countries. In the future under-developed countries will also join such developments. Hence, it is critical that concrete construction should be based on a sustainable basis to extend the limited resources available for future generations. The main drive is to "Reduce, Reuse & Recycle", the three pillars of sustainability.

Reduce implies achieving the same result with less in terms of materials, energy (carbon footprint) and human effects. In concrete industry, minimizing the use of Portland cement with supplementing cementitious materials (fly ash, ggbs & silica fume) lowers the carbon footprint of concrete. Another challenge is to design concrete for the same performance requirements with lower cement content, e.g. high strength concrete. However, this can only be achieved if the volume of concrete is reduced to an extent that compensates for the higher cement content with lower water/cement ratio in high strength concrete. Currently the limitation lies in the minimum water content to obtain the needed consistence (even with the latest generation of superplasticizing admixtures available). Lower water/cement ratio for higher concrete strength can only be realized with higher cement content. Hence the volume of higher strength concrete has to be reduced to the extent that the total amount of cementitious materials for the concrete structural element is sufficiently reduced. This posts the major challenge to designers for the structural concrete elements which should also include the amount of steel reinforcement required.

One changing approach in "Reuse" is to reuse structural components when an existing concrete structure is to be demolished (often for economic reasons, land cost) rather than its intended design working life. An example of such approach is reported in a study by Ong (2010) on "design for deconstruction" (DfD) jointly by the Housing and Development

Board of Singapore and National University of Singapore. The concept was validated with half-scale model beam elements joined as beams, deconstructed and reconstructed before load testing. In such applications, a completely new BIM system is also developed to store the original design information as well as the method of deconstruction and reconstruction with potential for longer beam spans.

Coarse recycled aggregate (RA) from demolition wastes may not be suitable for structural concrete production and to be assessed on a case-by-case basis. However, BS 8500 (2016) has adopted a new term "crushed concrete aggregate, CCA" to replace the previously more general term "recycled concrete aggregate, RCA". It is limited in the source of the concrete as part of the requirements for coarse crushed concrete aggregate. "Where the material to be used is obtained by crushing hardened concrete of known composition that has not been in use, e.g. surplus precast units or returned fresh concrete, and not contaminated by storage or processing, the only requirements are for aggregate size, fines content, drying shrinkage and resistance to fragmentation" as indicated in Table 2 of BS 8500-2 (2016). Limitations on the use of coarse CCA are given in Table 3 of BS 8500-2. The maximum strength class is C40/50 and for exposure classes of X0, XC1 to XC4, XF1 and DC-1. These are more demanding than for coarse RA.

There is no guidance on the use of fine CCA in concrete. However, Note 1 in BS 8500-1 (2016) 4.3.6 states that "Clean fine CCA is suitable for use in concrete". Concern is for presence of gypsum plaster which may not be absent for sources of concrete indicated in Table 2 of BS 8500-2 (2016) quoted above. Hence, "the use of fine CCA is left to the project specification, which can take account of the particular source of CCA" (4.3.6 BS 8500-2: 2016). Further studies on the characteristics of fine RA and fine CCA may lead to guidance being included in codes.

4.0 FUTURE DEVELOPMENTS

After the brief review of the historical PAST and some of the issues related to concrete at PRESENT, it leads to consideration of developments in the FUTURE.

4.1 Progress To-Date

The reliance of past track records and prescriptive approach in codes and standards for concrete has hindered innovative advances to be adopted in practice. Constituents for concrete and concrete technology have made significant advances over the past few decades (1980's to 2019). For example "Ordinary Portland Cement" in the past changes to the current 34 types of cement in BS EN 197-1 (2011) and in the future the low carbon footprint alkali-activated cementitious materials and concrete (PAS 8200: 2016). At early days, plasticizing and retarding admixture was based on lignosulfonates leached from the natural wood pulps in producing white colour paper. The latest generation of polycarboxylate is now an engineered product for which both plasticizing and set-retardation function can be specified for specific project requirements. Future development may include potential for enhancing corrosion resistance of embedded steel reinforcement. Fibre-reinforced composites are the newly fast developing structural medium. Recycled aggregate for structural applications is specified with a set of well defined requirements for coarse crushed concrete aggregate (CCA) and with the

potential also for fine CCA to be incorporated. Together with crushed stone fine aggregate, they will eventually replace the diminishing source of natural sand for concrete.

The traditional approach in specifying concrete and its constituent materials adopts mainly standard prescriptive assessment methods and acceptance criteria. In most cases, more often than otherwise, they rely on semi-empirical approach for conformity with little direct application to the site requirements. Hence, they mainly served the purpose of meeting the specified requirements which may not be those for the actual construction processes. There is a need to develop a more site performance-based system of assessment with target acceptance values related to the applications on site. Two such examples are presented to illustrate this change of emphasis. They serve to illustrate ways towards enhancement to the current standard test methods and may still need further refinements to meet the actual needs on site.

4.2 Passing Ability of SCC

For SCC the passing ability classes (PJ1 and PJ2 to BS EN 12350-12 2010) using the J-ring are based on two configurations of J-rings. They do not necessarily simulate the configuration of reinforcement bars in an actual structural element. Passing ability depends on two factors, the clear gap spacing between reinforcement bars and the extent of blockage by the reinforcement bars over a given sectional area (expressed as a blockage ratio), which is the factor not considered in BS EN 12350-12 2010). A modification of the J-ring of 300 mm diameter to one of 500 mm (P-ring for passing ability) enables a greater number of combinations of the factors, clear gap spacing and blocking ratio. This has been discussed by Tam (2019) based on the use of the P-ring reported by Chan *et al* (2010). An example is the case of a raft foundation with 40 mm bars at 100 mm centres in both directions resulting in a clear gap spacing of 60 mm and a blocking ratio of 40 % on site. With the P-ring, this is approximated with 16 x 40 mm diameter bars giving a clear gap space of 58 mm and blocking ratio of 41 %. On the other hand J-ring with wide gap has clear gap space of 59 mm but blocking ratio of only 23%. With a larger diameter of 500 mm for the P-ring, the concrete has reached a slower flow rate by the time it meets the bars compared to the case of the J-ring of 300 mm diameter.

The passing ability in the J-ring test is based on the difference in height of the concrete before and after it has flowed through the clear gap spacing and the blocking effect of the bars (J-ring step). This is disadvantaged by the fact of the small difference in J-step specified (≤ 10 mm) and the lack of repeatability (4.6 mm) and reproducibility (7.8 mm) for the clear gap spacing of 41 mm (BS EN 12350-12 2010). Tam *et al* (2005) proposed adopting the ratio of the P-ring flow diameter to the slump flow diameter as the Passing Ability Index (PAI). ASTM C1621 (2017) first published in 2007, also based the assessment on these two diameters to indicate the level of blockage but specified the difference between the two flow diameters. It defines the difference of (0 to 25 mm) as "no visible blocking", (> 25 to 50 mm) as "minimum to noticeable blocking" and (> 50 mm) as "Noticeable to extreme blocking". In the case of PAI, it takes into account the actual value of the value of the slump flow diameter. For example, when the slump flow diameter is 700 mm (mid-point of 550 to 850 mm), the corresponding ratios in PAI

are (1.00 to 0.96), (< 0.96 to 0.93) and (< 0.93).

4.3 Cold Joint Formation

The casting of raft foundations often calls for over 10,000 m³ of continuous placement of concrete taking up to over 2 days. In some instances, delay may arise from arrival of RMC delivery due to traffic accident/congestions or stoppage due to break down of pumping system. There is always the uncertainty how long such a delay can be tolerated before issues of potential cold joint formation which may impair the concrete quality in the zone making up of the already placed concrete with the fresh concrete to be placed over it. A definite cold joint is present between hardened concrete and newly placed fresh concrete for which the interface is treated to enhance the bond at the interface. However, it is less clear when the already placed concrete is only partially set. This uncertainty remains unresolved and there is as yet no method to assess the situation on site. A series of preliminary studies was initiated at NUS and some of the findings have been reported by Tam *et al* (2017). When the zone of concrete consisting of the already placed and newly placed concrete is vibrated the resultant effect is a reduction in the flexural strength determined by testing a vertically cast interface of a beam in flexure (modulus of rupture mode). No distinct line indicating a joint cold is observed. The delay time was up to 6 hours in the laboratory test. Although this finding does not resolve the issue at hand, but another finding as part of the study provided an approach to assess the state of the already placed concrete. Based on the current approach to determine the potential cold joint formation time using the ASTM C403 (2016) method, the time for the wet-sieved mortar from the concrete to reach a penetration resistance of 3.5 MPa, the corresponding penetration resistance of the same concrete was found to be approximately 10 MPa for the designed concrete tested. Since a single concrete was investigated, the equivalent penetration resistance of concrete is valid only for the designed concrete tested. However, the concept that the in-situ concrete already placed may be tested for its penetration resistance before newly fresh concrete is introduced may be adopted as an interim approach. By correlating the time for the wet-sieved mortar of project concrete to reach 3.5 MPa and the corresponding penetration resistance of the same concrete at that time, this may be taken as the criterion for expecting potential formation of a cold joint. This may serve as an interim measure until further investigations on the bond strength in the zone consisting of both already placed and newly placed concrete of different compositions. Other parameters may include treatment of the surface of the already placed concrete with bonding agents (including cement slurry) or by increasing the strength class of the yet to be placed new concrete for intermixing by internal vibrators to compensate for the reduction of strength noted in the study. Alternatively, acceptance criterion for an approved delay based on performance testing of flexural strength considered in the study as part of the initial tests of the designed concrete may be developed.

4.4 Carbon Dioxide Challenge

The production of Portland cement is accompanied by a significant generation of carbon dioxide. Although recent advances in cement production technology has reduced the amount of carbon dioxide released from the former level of 1,000 kg per ton of

cement to around 800 kg, due to increasing demand in cement for concrete in economic development, this presents a challenge to minimize global warming. Injection of carbon dioxide into readymixed concrete was a new technology founded by R. Niven of CarbonCure Technology in 2007. The CO₂ introduced during production has been shown to benefit some properties of concrete, such as strength and durability (Monkman *et al*, 2016). As a mitigating approach, new technologies are developed in relation to carbon dioxide sequestration in cementitious construction materials. Carbonation of concrete is a well known phenomenon which occurs naturally during the service life of concrete. However, the amount of carbon dioxide removed from the atmosphere in this process is not significant compared to the amount released in cement production for the concrete. The new approach is to induce carbonation in concrete by curing concrete precast elements under high concentration of carbon dioxide and pressure/temperature to accelerate the carbonation process. In this way, sequestration of carbon dioxide from industrial processes such as burning of coal for energy generation can be captured to avoid being released to the atmosphere. A recent publication on this field edited by Pacheco-Torgal *et al* (2018) reported on the development of this technology.

4.5 Assessing Performance of Mortar in Lieu of Concrete

The study on concrete performance may be based on the mortar fraction of the concrete (e.g. setting time of concrete with wet-sieved mortar). The combined effect of grading, particle shape and surface texture of fine aggregate on consistence may be assessed based on mortar with adjustment of plasticizer dosage needed for a given consistence. The concept is already practiced in admixture usage with a standard mortar. A new approach is proposed by testing mortar using a modified procedure in the flow table test for consistence of concrete. The initial slump or flow diameter is an indication of the yield strength. The subsequent increase in the flow diameter by increasing number of jolts of the flow table is an indication of the plastic viscosity, analogous to concept in the Bingham model for rheology of concrete. The results will be reported at a later date.

5.0 CONCLUDING REMARK

In summary, in order to have sustainable concrete construction in the FUTURE, it calls for:

- (a) Urgent establishment of durability monitoring of existing and new infrastructures to enable calibration of explicit durability design equations for carbonation and chloride ingress.
- (b) Develop usage of marginal aggregates for concrete such as both coarse and fine RA and RCA
- (c) Develop design criteria for design with concrete using low carbon footprint cementitious binders.
- (d) Develop truly performance-based assessment methods for both conformity testing in laboratory and their corresponding test methods for site application.

- (e) Develop low carbon footprint cement using SCM from other industries
- (f) Develop methods for the sequestration of carbon dioxide in concrete. ■

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THE IMPACT OF DIRECT LIGHTNING STRIKE DAMAGES ON PV MODULES IN A LARGE MALAYSIAN PV FARM

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ABSTRACT

Many lightning risk analyses avoided considering the role of the PV Module's aluminium frame as a natural lightning air termination system or if such a role is considered, assumed that the 'thin' aluminium frame, would not be damaged from metal melting and evaporation at the point of lightning stroke attachment. Although the IEC 62305 is not lacking in guidance on the use of thin metal sheets as air terminations, this aspect is not considered in PV farm design. To ensure correct inputs into the risk assessment calculation, the evaluation of interception and sizing efficiencies and the damage probabilities of the natural components have to be addressed. A comparative analysis is done between two types of air terminations; the PV-frame LPS and the finial-added LPS. The result indicates that for solar PV farms exceeding a certain size and operating in high ground flash density regions like Malaysia, the finial air termination may out-perform the PV-frame LPS.

Keywords: Lightning Protection System, Interception Efficiency, Hot-spot Puncture, Sizing Efficiency, PV Module Damage Rate, PV Module Replacement Rate

1.0 INTRODUCTION

The IEC 62305 method which was originally intended for lightning protection of buildings and structures, has been adopted by the Malaysian Solar PV Industry as the basis for PV farm lightning risk analysis. Many of such analyses avoided considering the role of the PV Module's aluminium frame as a natural lightning air termination system or if such a role is considered, assumed that the 'thin' aluminium frame, would not be damaged by thermal melting and metal evaporation at the point of stroke attachment. Such assumptions have guided the risk analysis of smaller MW-output solar PV plants. Also for cost-saving reasons, lightning protection system (LPS) design would inevitably make use of the PV string support structures and foundations and their metal frames as a natural-component system. While the IEC 62305 is not lacking in guidance on the use of thin metal sheets as air termination, many risk analysis are accompanied by a lesser emphasis on the air termination interception and sizing efficiency checks. Consequently, the damage probability of the natural components is not accurately determined. To ensure correct inputs into the risk assessment calculation, the evaluation of interception and sizing efficiencies (IE and SE respectively) and the damage probabilities of its natural components, have to be addressed.

The purpose of the work reported here is to determine both the interception efficiency of the LPS and sizing efficiencies of the natural components, estimate the damage rate, discuss its implication on and improvement of the performance of the lightning protection system and how much it impacts the PV farm's service life in terms of its mean-time-to-failure, MTTF and its PV module replacement rate which is a factor in cost calculation.

2.0 SIZING AND INTERCEPTION EFFICIENCIES OF THE LPS

The IEC 62305-1 [1] recognizes two causes of damages. The first is due to mechanical stress, arcing and overheating by high stroke currents. The second is due to shielding failure from weak first strokes. The first cause is represented by the LPS sizing efficiency, SE or by sizing failure rate, $SF = 1 - SE$. The second cause gives rise to overvoltage due to stroke penetration and can be expressed as shielding failure rate, $SFR = 1 - IE$. Both SE and IE must have near 1.0 efficiency if damage probability is to be near zero. Tables 3, 4 and 5 of Reference [1] gives the CIGRE data for the derivation of damage probability for LPL 1 to LPL 4. The derivation is reproduced in Table 1 below.

2.1 Sizing Efficiency, SE of the Aluminum Frame

From Table 1 and Figure 1, the SE of LPS Class I due to a large 200 kA ($I > 200\text{kA}$, prob. $\leq 1\%$.) stroke is $100\% - 1\% = 99\%$ or 0.99 pu. Thus, its sizing failure rate, SF = 1% or 0.01 pu.

Sizing efficiency, SE is determined from a number of stroke parameters representing the various failure mechanisms at the point of strike. They are given in Table D1 of Reference [1]. There are two thermal mechanisms, i.e. resistive heating and arc-root melting. Of particular significance to the PV module aluminum frame is the thermal damage resulting from the more dominant and severe arc-root melting at the immediate region around the stroke attachment point. Reference [1] recognizes this and uses a thermal arc-root voltage drop model for evaluating the arc-melting effects that cause metal punctures and hot-spots.

Table 1: IEC 62305 Damage Probability from Reference [1]

Parameters	Lightning Protection Level/ LPS Class			
	I	II	III	IV
Sizing Efficiency, SE	0.99	0.98	0.95	0.95
Interception Efficiency, IE	0.99	0.97	0.91	0.84
Total Efficiency	0.98	0.95	0.90	0.80
Damage Probability, P_B	0.02	0.05	0.10	0.20

Note: $P_B = 1 - IE \times SE$

2.2 Interception Efficiency, IE of the LPS

The interception efficiencies in IEC 62305 are directly derived from the CIGRE Stroke Current Cumulative Distribution as shown in Figure 1. In Table 1, they are equated to the stroke current probabilities for the various LPS without the rigor of probabilistic Rolling Sphere Method (RSM) analysis. As such from Figure 1 for LPS I, a shielding failure rate (SFR) due to 3kA stroke current is $1 - 0.99 = 0.01$ pu which implies a 0.99 pu or 99% interception efficiency as shown in Table 5 of Reference [1]. The assumption is then made that a shielding failure from even a low current stroke will always lead to damage from a large shielding failure overvoltage.

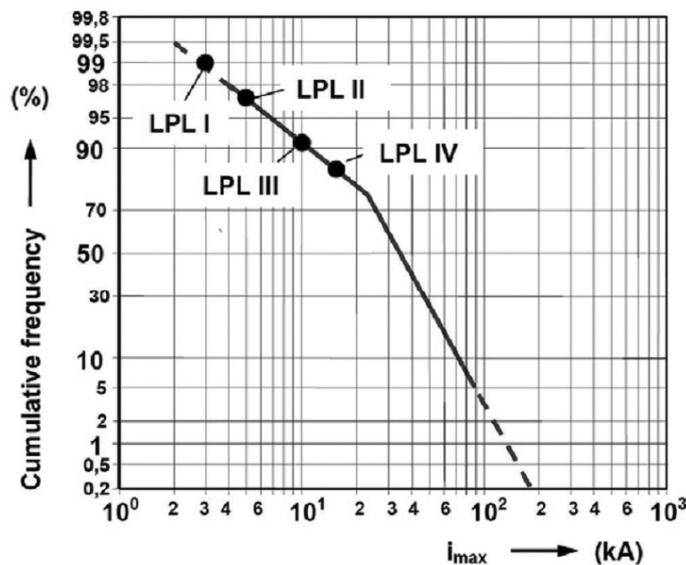


Figure 1: CIGRE Stroke Current Cumulative Probability Distribution

2.3 Damage Probability, P_B of the PV Module

In practice, the damage probability, P_B is derived according to the formula given under Table 1. Using it, automatically assumes that the sizing efficiency of the natural air termination components is near 100%. Table B.2 of Reference [2] gives the damage probabilities, P_B either for not providing any lightning protection measure (LPM) or for providing one of the four IEC 62305 type LPS. Although Reference [1] allows for detailed investigation taking into account the requirements of sizing and interception criteria, this is usually not done. When a natural air termination component is used, Table 3 of Reference [3] points to a minimum aluminium sheet thickness of 7 mm in order to avoid puncture, hot-spot or ignition problems. Thus, as shown in Figure 2, the thin aluminium frames are possible sites/locations of physical damage on the exposed PV modules. They may also present life safety hazards in the PV farm.

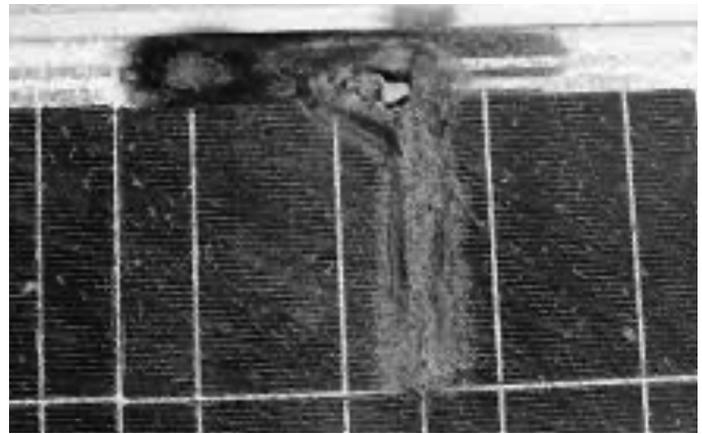


Figure 2: Damaged PV Module Aluminum Frame Caused by Lightning Stroke Attachment

3.0 THE PV FARM DAMAGE PROBABILITY

3.1 Interception Efficiency of Finales

The accuracy of the LPS interception efficiency estimate can be improved by carrying out probabilistic RSM evaluation of a typical LPS design. Reference [4] examined this by using a dynamic electro-geometric model (DEGM) in a probabilistic analysis to derive representative estimates of IE. The results for a finial-based LPS system is summarised in Table 2.

Table 2: Interception Efficiencies of Air-Termination Rod Systems for Rod Separation Distances, d Derived from DEGM [4]

LPS Class	Interception Efficiencies of Air-Termination Rods placed at Roof Corners, Edges and Centre in % for Separation Distance, d m and in brackets, min. rod height, h m			
	d = 5	d = 10	d = 20	d = 40
I	99.97(0.3m)	99.97(1.3m)	99.96 (5.9m)	-
II	99.92(0.2m)	99.92(0.9m)	99.93(3.6m)	99.74(20m)
III	99.83(0.15m)	99.84(0.6m)	99.81(2.3m)	99.79(10m)
IV	99.53(0.1m)	99.56(0.4m)	99.64(1.7m)	99.65(7.1m)

Table 2 shows the typical DEGM IE estimates based on the separation distance of the air-termination rods. The IE values lie within a narrow range of 99.5% to 99.9% as compared with those in Table 1. The DEGM allows the IEs to be improved;

more precisely, by a combination of the finial height, h and finial separation, d . The results show that by probabilistic analysis with RSM, the likely IE may be > 0.995 , giving a SFR < 0.005 . Comparison between Tables 1 and 2 seems to suggest that the DEGM presents some possibility to adopt IE values higher than those of the IEC LPS classification.

To achieve an IE of at least 99.5% in actual application to a PV farm, Table 2 suggests that the rods/finials should be long enough ($h > 0.3\text{m}$) and positioned dense enough ($d < 10\text{m}$ separation) in the farm. However, shading avoidance requires h to be short. Thus, this criterion puts a limit to the finial's maximum height, say to less than 1.3 m.

In other words, for a conservative IE = 0.995, the PV farm LPS design can be guided by two conditions:-

1. Finial Height, h : 0.3 - 1.3 m
2. Finial Separation Distance, d : less than 10m

When bounded by these two conditions, the LPS design need not be type-classified. However, as required in all new designs, it is prudent to complete a probabilistic EGM analysis of at least, a representative multiple PV string block of a new PV farm.

3.2 Damage Probability of the PV Module Aluminum Frame

If the efficiency of an LPS's air termination is IE, its PV damage probability, $P_{BI} = IE \cdot P_{HS}$ where P_{HS} is the air-termination's hot-spot damage probability. In maintaining high IE, it becomes prudent to ensure that the air-termination's hot-spot damage probability, P_{HS} is small.

In practice, the top layer of the PV module aluminium frame naturally acts as a mesh air termination network. Without any added external air termination, lightning strokes will terminate on the rectangular meshes. Normally, the aluminium metal is only about 1.5mm - 2mm thick as shown in Figure 3. Such a thin layer would not serve well as air-termination because stroke termination on the aluminium mesh could result in deep melts and high temperature at its opposite underside to cause damage to the PV contact surface [5]. The damage probability of the aluminium layer can be estimated by using a 2-phase thermal arc-root voltage drop model given in the IEC 62305 [1] and applied to the probability distribution of lightning flash charges.

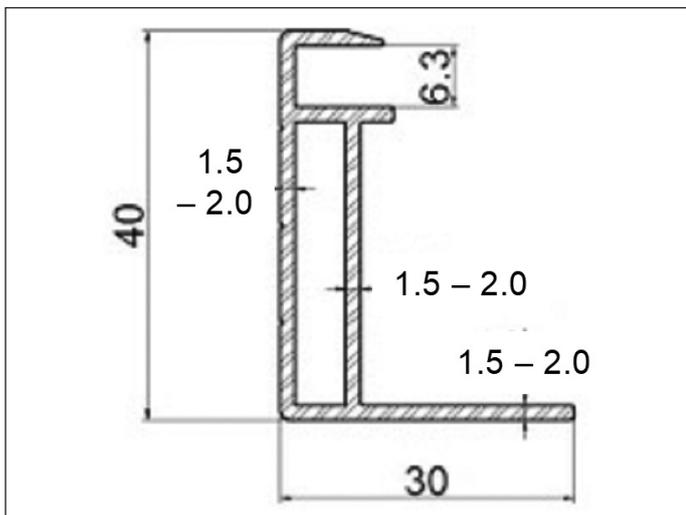


Figure 3: The Structure and Typical Thickness, in mm of PV Module Aluminum Frame

The volume, V of melted metal of a thin sheet is a function of arc-root voltage drop, U and equivalent charge transfer, Q :-

$$V = \frac{uQ}{\gamma(C_w(\theta_s - \theta_u) + C_s)} \quad (1)$$

where

V is the volume of metal melted, (m^3)

U is the arc-root voltage drop (assumed constant),
(= 10 V for anode [6])

Q is the effective charge of the lightning current, (C)

γ is the aluminium density, ($2,700 \text{ kg/m}^3$)

C_w is the thermal capacity of aluminium, (908 J/kg.K)

θ_s is the melting temperature of aluminium, (658°C)

θ_u is the ambient temperature, (32°C)

C_s is the latent heat of melting of aluminium, ($397 \times 10^3 \text{ J/kg}$)

Other parallel mechanisms of resistive heating, vaporization, radiation, etc. are small compared to melting. Resistive heating comes from the flow of lightning surge current whereas arc-root plasma melting comes from the lightning charge transfer over a long duration of 0.5 seconds. Arc-root melting is dominant in the charge transfer mechanism. Thus, an estimate of the total charge transfer can be made by using a melting efficiency factor to account for losses from metal sputtering or ablation and the other parallel mechanisms. Guided by [5] and [7], it is estimated to be 87.5%. Thus, the long duration lightning charge transfer to produce total melting effects that are partly represented by Q is $Q_L = \frac{Q}{0.875}$.

Following the spot-melting model of [8], the metal volume of the single spot that is melted by the effective charge, Q is approximated by a hemisphere with a radius equal to the thickness of the aluminium. It represents a single-spot melt-through volume, V and excludes metal loss in sputtering or ablation around the spot itself.

The cumulative probability of the total negative lightning charge, Q_L including subsequent stroke charges that are transferred to the spot is given in [5] and [9] as :-

$$P = \frac{1}{1 + \left(\frac{Q_L}{7}\right)^{1.7}} \quad (2)$$

Thus, the derived lightning charge, Q_L can be used to estimate the probability of it being exceeded. A smaller charge will lead to a higher damage probability. This probability can be taken as the sizing failure probability. Table 3a gives the calculated lightning charge probability which is equated to the frame's hot-spot damage probability, P_{HS} . The hot-spot damage probability, P_{HS} is equal to 0.6399. When it is combined with a high IE, the LPS damage is not tolerable.

Table 3a: Calculation of Damage Probability of Aluminum Frame

Input	Aluminium
Ambient Temperature, C	32
Arc-root Voltage Drop, V	10
Metal Thickness, mm	2
Melting Efficiency, pu	0.875
Melt Volume, $V \text{ mm}^3$	16.755
Effective Charge, C	4.367
Lightning Charge, C	4.991
Lightning Charge Probability	0.6399

Table 3b shows the reduction in damage probability with increase in aluminium thickness. It confirms that the IEC 62305 recommendation of 7 mm aluminium thickness is reasonable; its hot-spot damage probability is 0.003. Table 3b suggests that to reduce P_{HS} , the thickness of the aluminium layer has to be increased. To do so is costly. A more cost-effective engineering solution may be achieved by adding to the natural-component LPS, steel finials arranged according to the criteria developed in the previous section. Their role is to preferentially intercept lightning strokes and achieving high IE (99.5%). The aluminium mesh's role can then be relegated to an Electromagnetic (EM) screening function.

*Table 3b: Hot-spot Damage Probability vs
Aluminium Frame Thickness*

Aluminium Frame Thickness, mm	Hot-Spot Damage Probability, P_{HS}
2	0.6399
3	0.1835
4	0.0493
5	0.0163
6	0.0065
7	0.0030

4.0 EVALUATING THE LIGHTNING DAMAGE RATE OF A PV FARM

The PV farm structure is characterised by an extensive low-height and isolated-surface area. It physically resembles a shielded open-structure since the PV modules are made of aluminium frames which are bonded and earthed. Naturally and inevitably, the frames act as LPS mesh networks. Most stroke terminations are characterized by S1 overhead downward flashes with little or no side stroke terminations. Shielding failure is influenced by finial height and finial positioning or the lack of them. Cost-saving considerations compel the natural components of the PV module support structure and foundations to be used as the LPS down-conductor and earth systems as shown in Figure 4. Using their large metal cross-sections to distribute the large stroke current help reduce resistive heating effects and would not contribute to damage.

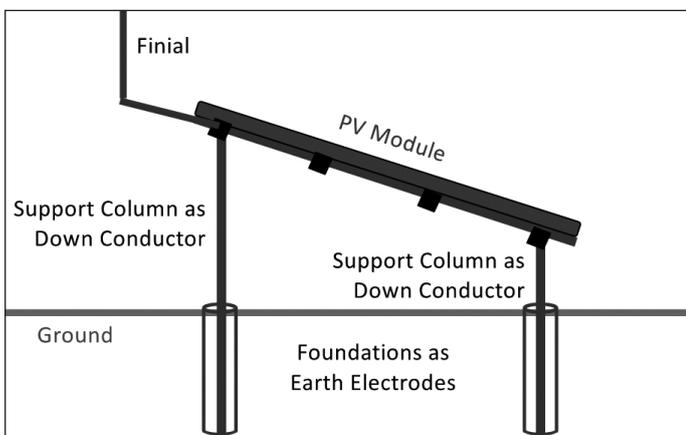


Figure 4: PV Module Support Structure Acting as LPS

For a PV farm, there are two damages; one, P_{B1} arising from successful stroke interception and the other, P_{B2} from shielding failure. The total damage probability of a PV farm is thus:-

$$P_B = P_{B1} + P_{B2} \quad (3)$$

where

$P_{B1} = IE.P_{HS}$ P_{HS} is the hot-spot damage probability of the air termination

$P_{B2} = (1-IE).P_{OV}$ P_{OV} is the damage probability of the protected PV surface due to overvoltage.

Based on the above equation, the damage probabilities are calculated in Table 4 with $IE = 0.995$ for two LPS air terminations. One is obtained by adding external steel finials to the natural component LPS. The other makes use of the available PV module aluminium frames as air termination in an effort to save cost.

The cause of large P_{B1} is the high hot-spot probability, P_{HS} due to metal melting. Its value was inaccurately taken to be small in many risk analysis calculations and it led to the selection of the PV-frame LPS as a techno-economic solution in many instances.

Shielding failure does not always lead to damage if the PV module impulse withstand voltage is high. Laboratory tests have shown that certain c-Si PV modules can withstand up to 35 kVp impulse voltage without damage [10]. With limited data, P_{OV} is taken to be 0.5. The results of the damage rates show that the contribution to P_B improvement from impulse overvoltage withstand is small in both cases. P_{OV} contributes less significant improvement if P_{HS} is large as in the case of the PV-frame alternative.

*Table 4: Lightning Damage Rate for Various
Air Terminations And PV Module Impulse Withstand*

LPS Air Termination	14mm Dia. Steel Finials	2 mm Aluminium Frame		
Interception Efficiency, IE	0.995	0.995	0.995	0.995
Hot-Spot Damage probability, P_{HS}	0.005	0.005	0.6399	0.6399
$P_{B1} = IE.P_{HS}$	0.004975	0.004975	0.6367	0.6367
Shielding Failure Rate, SFR = $1-IE$	0.005	0.005	0.005	0.005
PV Surface Damage Prob., P_{OV}	1.0	0.5	1.0	0.5
$P_{B2} = (1-IE).P_{OV}$	0.005	0.0025	0.005	0.0025
$P_B = P_{B1} + P_{B2}$	0.009975	0.007475	0.6417	0.6392

The larger damage rates pertaining to the aluminium frames have to be reduced because PV failures lead to loss of production and increase in maintenance and replacements which may cost more than the initial cost saving during construction. The result points to the need to reduce P_{B1} which implies reducing P_{HS} . Since the aluminium frame thickness cannot be changed, a viable improvement is to add short external finials to the natural-component LPS.

5.0 LIGHTNING PROTECTION PERFORMANCE OF THE LPS

Following the IEC 62305 method, the annual number of dangerous events due to lightning in tropical Malaysia is calculated on a per MW_{ac} output basis by using a land-use intensity of around 4 acres/MW_{ac}, a PV module surface area utilization parameter expressed as 2.063m²/350W, and a ground flash density of 30 flashes/km²-year. The PV module surface area utilization parameter allows the number of dangerous events to be calculated for different PV modules. The ground flash density (GFD) is calculated from CIGRE's formula [11] since the IEC 62305 GFD formula is only applicable to temperate regions. Using the IEC 62305 method of calculating annual dangerous events, a rate of 0.432 dangerous events/year-MW_{ac} is derived. It is noted that this value is proportional to the PV module surface area utilization parameter and to the GFD.

If the output of the PV farm is S MW_{ac} and it is protected by an LPS system giving a damage rate of P_B, then the estimated annual lightning damage, N_{DB} of the solar PV plant is given by:-

$$N_{DB} = 0.432 \times P_B \times S \tag{4}$$

N_{DB} can be interpreted as the average damage rate of PV modules. N_{DB} is small if the GFD is small, as in temperate regions.

Based on the above equation, the estimate of the PV farm's mean-time-to-failure (MTTF)

$$MTTF = \frac{1}{N_{DB}} \tag{5}$$

Table 5 compares the lightning protection performance of the finial-added LPS with that of the PV-frame LPS.

Table 5: Comparison of LPS Performance (Annual Damages and MTTF)

Plant Size, MW _{ac} Output	Annual Damages		Mean-Time-To-Failure, years	
	14mm Dia. Steel Finials	2 mm Aluminium Frame	14mm Dia. Steel Finials	2 mm Aluminium Frame
1	0.0043	0.277	232	3.61
2	0.0086	0.554	116	1.80
5	0.0215	1.386	46.4	0.721
10	0.043	2.772	23.2	0.361
15	0.0646	4.158	15.5	0.240
20	0.086	5.544	11.6	0.180
30	0.129	8.316	7.74	0.120
50	0.215	13.86	4.64	0.072
100	0.431	27.72	2.32	0.036

The two parameters, annual PV damage and MTTF, are used for comparing the finial-added LPS with the PV-frame LPS. For LPS selection, it is reasonable to establish the following technical criteria:-

1. Accept Alternative if its average damage rate, N_{DB} < 1.0 per year
2. Accept Alternative if its MTTF > 1.0 year.

The finial-added alternative meets both technical criteria for power outputs up to 100 MW_{ac} but the PV-frame alternative could meet the technical criteria up to 3.6 MW_{ac} for a GFD = 30. Without finials added, the PV-frame alternative is cheaper. Hence, based on technical criteria, the PV-frame LPS could be selected for Solar PV farms of size 3.6 MW_{ac} and below. In regions

experiencing smaller GFDs, the acceptable size of the PV-frame LPS increases. For example, if the GFD = 10, then the maximum size of the PV-frame alternative may be 10 MW_{ac}.

6.0 LONG TERM OPERATION & MAINTENANCE IMPACT FROM LPS

Based on the results, an O&M impact study can be performed to address the number of occasions PV-module replacement have to be made over the service life of the plant. It is assumed that each replacement occasion will have at least one PV module replaced. Collateral damage may increase the number of PV modules in each occasion. With spare PV module stock, the mean-time-between-failure (MTBF) can be assumed to have a negligible replacement duration. It approximates the MTTF. Given the plant service life is L years, the number of occasions that PV modules need replacement from lightning damage is given by:-

$$\text{Integer } (L/MTTF) \tag{6}$$

Table 6 shows the long-term impact on operation and maintenance as measured by the number of occasions of PV module replacement.

Table 6: No. Of Replacements Over Service Life

Plant Size, MW _{ac} Output	No. of Replacement Occasions in 21 years	
	14mm Dia. Steel Finials	2 mm Aluminium Frame
1	0	5
2	0	11
5	0	29
10	0	58
15	1	87
20	1	116
30	2	175
50	5	291
100	9	583

For 21-years operation, large solar PV plants should not rely on the PV aluminium frame for lightning interception as they will require extensive replacement efforts. The provision of finials to the existing natural-component LPS improves the operation and maintenance situation tremendously by diverting the lightning strokes to them. If the average number of replacements is limited to say, once in 2 years, then a maximum of 10 replacements is allowed for a 21-year plant service life. In this case, the maximum acceptable plant size for the PV-frame LPS is less than 2 MW_{ac}. Thus, operation and maintenance requirements must be considered in the selection of LPS type. It may turn out that PV module replacement rate is the dominant and significant consideration in LPS selection for a PV farm.

With the estimated number of replacement occasions, a cost evaluation for the alternatives can be made. It then leads to the third selection criterion which is based on cost:-

3. Compare the total (additional capital cost, PV module replacement cost and loss of revenue from damages) costs and select the less costly alternative.

7.0 CONCLUSION

The solar PV farm lightning protection risk analysis can be updated with improved IE estimates. Progress in interception efficiency calculations points to a generally higher IE from finials than what is used in IEC 62305. Another critical factor that determines the performance of LPS is the sizing efficiency of the air termination. While the PV module aluminium frame may be used as a mesh-type air termination to save cost, caution is needed in their selection for operation in a high GFD region because its sizing efficiency is reduced by its thin aluminium thickness. This SE reduction is attributed to hot-spot melting of the metal at the point of lightning stroke attachment which results in damage to the PV contact surface at the frame's underside. An estimate of its damage rate has been demonstrated using the arc-root voltage drop model given in IEC 62305. It points to the importance of damage rate calculation and of bringing the calculated value into the lightning risk assessment routine.

Based on the estimates of IE and SE, the PV module's damage rate can be estimated. With them a comparative analysis can be made between the PV-frame LPS and the finial-added LPS. Preliminary results indicate that for solar PV farms exceeding a certain size and operating in the Malaysian climate, the finial-added air termination may be a cost-effective alternative. It also outperforms the PV-frame LPS by achieving a low damage rate and by meeting operation and maintenance requirements better. The technical performance and operation advantages may outweigh the additional construction cost for solar PV farms when their outputs exceed a certain size. This gives the PV Industry the opportunity to decide on the critical plant size after taking into consideration the cost criterion. ■

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PROFILES



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ASSESSMENT OF RAILWAY SAFETY IN SOUTHEAST ASIA REGION

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ABSTRACT

This paper reports on the railway safety in Southeast Asia based on rail accidents and incidents trends. Rail transportation has many benefits, it includes fixed routes, cost-effective, safe and large capacity. It is also every country's major means of transportation. However, there are less research on causes of rail accidents and incidents, despite rail risk assessments being conducted in Great Britain, Finland and Japan. In Southeast Asia, there is no investigation for predicting rail accidents and incidents. Hence, it is vital to study the railway safety risks in this region. Data reporting is based on news or reports published for public reviews. After performing Trend Analysis, robustness is evaluated in prior to perform risk analysis using Delphi technique. Following risk analysis, the Analytic Hierarchy Process (AHP) technique-based railway safety rank is carried out which is designed by the Authors of this study. The variables are based on total number of cases and fatalities, level of robustness and risk. Ranking countries from high-risk to low-risk, the rank are as follows; Thailand, Indonesia, Vietnam, Myanmar, Philippines, Malaysia, Cambodia and Singapore.

Keywords: Southeast Asia; Railway Safety; Railway Accidents; Railway Incidents; Railway Engineering

1.0 INTRODUCTION

Rail transportation has been one of the oldest land transportations in the world. The earliest form of rail transport began in the sixth century BC near Corinth in ancient Greece. It was a system called 'Diolkos' with a 7 km-long stone-paved portage trackway that enabled boats to be moved overland across the Isthmus of Corinth on a trolley hauled by manpower along a curved route that avoids steeper gradients. The main purpose for rail transportation back then was solely focused on transferring industrial goods such as coal and ore to the warehouse and port (Lewis, 2001). As time advanced, rail technologies have evolved themselves; for instance, from hand power to horse power, wooden rails to metal rails and steam engine to electric-powered engine. As railway became the key component to swift movement of products and labor required by the industrialization that time, the transportation then expanded to the purpose of moving people to their desired destination (Spiryagin *et. al.*, 2016). As for now, rail transportation can be represented as a mode of land transportation that transfers people and goods on wheeled vehicles running on rails. Hence, it has become the most effective public transport system and each country's most significant transportation mode. This is due to the fact that rail transportation comes with a lot of advantages. Not only rail transportation is the most dependable mode of transportation as it is least effected by weather conditions unlike other modes of

transportation, it is also better organized due to its fixed routes, more economical, safe and has large carrying capacity.

Since 1941, the risk assessment related to the rail industry had been carried out. Until now, the assessment focused only on collision with warning devices and track features as a factor or criterion at the railroad crossing (Ismail, 2016). It is, however, less researched in terms of factors leading to rail accidents and incidents, especially in Southeast Asian countries. Given that each nation in Southeast Asia has a different geographic and running rail system in its networks, it is difficult to develop a prediction model to investigate their independent variable or factor effect. Therefore, in Southeast Asia countries, there is no clear investigation method for forecasting rail accident and incidents. In vieabove-mentioned facts, the aim of the present study is to review the safety risin the railway system among the Southeast Asian countries. Eight countries are included in this study: Myanmar, Cambodia, Indonesia, Malaysia, Philippines, Singapore, Thailand and Vietnam.

2.0 LITERATURE REVIEW

Rail accidents and incidents are major contributing factors to the interruption of train services and operations. The Federal Railways Administration (FRA) reports more than 300 causes of accidents, including infrastructure defects, rolling stock failures,

human factors, and other causes (Liu *et al.*, 2018). Railways are subject to many different types of hazards, and a wide range of safety measures mitigate the risks. Railway operators and regulators have long acknowledged that some safety measures provide better value for money than others, but the railways have not implemented traditional cost-benefit analysis (CBA) as widely as highways for evaluating safety measures. The common image of a rail accident is a multi-fatal train crash or derailment, but the majority of road accidents are more prevalent (Evans, 2013). There are four major groups of accidents which are train accidents per train-kilometer, personal accidents per train kilometer, level crossing (LC) accidents per year and trespasser fatalities per year which represents the medium-term trends in accident or fatality rates.

The words "Accident / Incident" are used to describe the entire list of reportable events, referring to the "Federal Railroad Administrative Office for Safety Analysis (FRA)." These include crashes, derailments and other events involving the operation of track equipment and causing reportable harm above an established threshold, impacts at crossings between railway on-track equipment and highway users, and any other incidents or exposures that cause any person to be killed or injured, or an occupational illness to a railway employee. Such terminologies are divided into three major reportable categories (FRA, 2015):

- 1) Train Accidents: A safety-related event involving on-track rail equipment (both standing and moving).
- 2) Highway-rail grade crossing incidents: Any impact between a rail and highway user (both motor vehicles and other users of the crossing as a designated crossing site, including walkways, sidewalks, etc., associated with the crossing).
- 3) Other incidents: Any death, injury or occupational illness of a railroad employee that is not the result of a "train accident" or "highway-rail incident".

2.1 Southeast Asian Railway Issues

In Southeast Asian region, each country faces their own challenges and issues as each of them have different trains and operators. Table 1 presents all the issues faced by every countries' railway system in Southeast Asia region.

2.2 Robustness of Railway System

Robustness is a term where it refers to a railway system with good train and track quality which do not break down easily. This can apply to a system with a high degree of safety where incidents rarely occur and where few people are injured. It can also mean a system with an extensive network and several lines where, if there is a disruption, passengers can easily be diverted. (Andersson, 2014).

In different ways, this type of robustness can be formally described: As defined by Salido *et al.* (2008), it is "the ability to resist to 'imprecision'", by Policella (2005), it is the tolerance for "a certain degree of uncertainty" and the capability to "cope with unexpected troubles without significant modifications" by Takeuchi and Tomii (2005). Although a delay analysis generally explains and analyses the causes and locations for delays, a rigorous analysis focuses on the recovery capabilities and how the inserted margin time can be used operationally. (Andersson 2014).

According to Dewilde *et al.* (2011), in the event of minor delays, a robust schedule minimizes the actual travel time of passengers. The ability to limit secondary delays and ensure

fast recovery times are necessary, but not sufficient, according to the authors, to establish a robust timetable. With respect to passengers, Schöbel and Kratz (2009) defined robustness and used the maximum initial delay possible without violating any transfers for the passengers as a robustness indicator.

Hence, from the definition above, it can be concluded that the higher the robustness of a railway network, the higher the safety level of the railway system. To further understand what is meant by robustness in railway engineering, it is depicted by Figure 1 where high robustness can be seen in Greater Kuala Lumpur. The red nodes are rail stations and red lines are the railway lines.

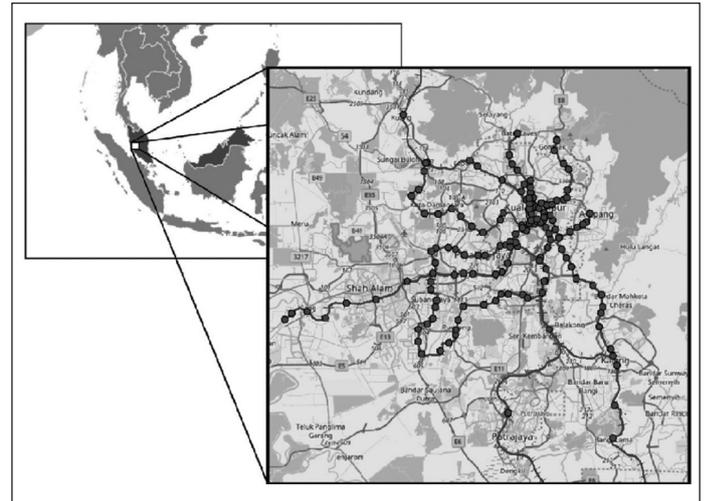


Figure 1: Robustness of railway network in Greater Kuala Lumpur (Ding, R *et al.*, 2018)

3.0 METHODOLOGY

The scope of this study mainly focuses on the case study of railway accident and incidents based on news or reports that had been publicly announced and published for public reviews such as The Bangkok Post (Thailand), The New Strait Times (Malaysia) and The Jakarta Post (Indonesia) in Southeast Asia. The countries include are Myanmar, Cambodia, Indonesia, Malaysia, Philippines, Singapore, Thailand and Vietnam.

Therefore, the method will be used in collecting data is called "data reporting". Data reporting is the process of collecting and submitting data which gives rise to accurate analyses of the facts on the ground. The case study reports will be covering from the year 2000 until 2020. However, the data for 2020 is only until the first quarter of the year. This selection was made due to the fact that no railway risk profile is made based on Southeast Asian countries' rail accidents and incidents.

Through the process of performing analysis, robustness assessment of each country's railway system is being done to further determine the risk of the railway system which is referred as Delphi technique risk analysis. In this study, a three-point scale risk scale to simplify the risk analysis. The three-point scale risk is shown in Table 2 with its probability and impact.

Breaking down the data into deeper level, it is expected to find the contributing factor to railway accidents and incidents. Then lastly, the country's railway safety is ranked based on a technique called Analytic Hierarchy Process (AHP). AHP is a multiple-criteria decision-making tool. This is an Eigen value approach to the pair-wise comparisons. It also provides a methodology to calibrate the numeric scale for the measurement

of quantitative as well as qualitative performances. Hence, the total number of cases, fatality number, level of robustness and level of risk will be the criteria in the AHP designed by the researchers themselves as shown in Figure 2.

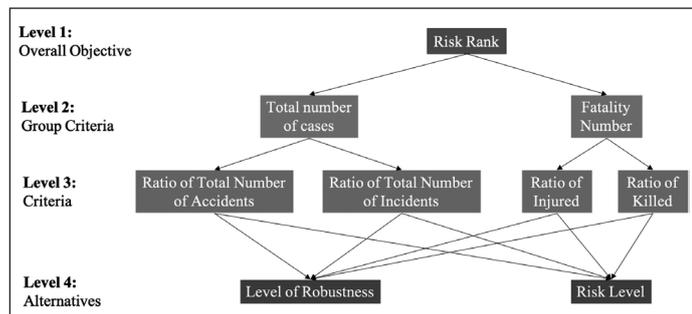


Figure 2: Analytical Hierarchy Process in determining the railway risk rank of a country

To demonstrate how the AHP for this study is being used, the country Thailand will be used as an example.

For Thailand, the total number of cases is 76 with a fatality number of 571 where 87 passengers were killed and 484 passengers were injured in the past 20 years. Focusing on the number of cases first, the ratio of a total number of accidents and the ratio of the total number of incidents is 84.44% and 15.56% respectively. It can be seen the ratio of total number of accidents is higher for Thailand which is a risk. For the ratio of casualty and ratio of injured, they are 15.24% and 84.76% respectively. Even though the ratio of casualty is lower, we are focusing on the number of accidents. Despite the ratio of casualty and ratio of injured are contrary to each other, people still were affected by the rail accidents in Thailand, and hence, adds another risk.

When it comes to the level of robustness in Thailand, it is without a doubt the robustness is high as the coverage of railway network is wide. However, the higher the level of robustness, the higher the safety system of railway system which is happened otherwise in Thailand. This is also adds another risk. Hence, that is why Thailand is ranked first in the risk rank of railway safety in Southeast Asian region.

Table 1: Railway system’s issues of every country in Southeast Asia region

Country	Reference(s)	Issues	Cause of Issue
Cambodia	Irigoyen (2017)	<ul style="list-style-type: none"> The Cambodian railways were in a poor physical condition because of war damage and decades of neglect. The last 48km of track towards the border with Thailand had been destroyed during the civil war. 	War damages and neglect.
	Transport & Logistics News (2010)	<ul style="list-style-type: none"> Railway traffic was declining because of the poor condition of tracks and equipment, which rendered the railways increasingly unreliable and slow. The staff of the Royal Railways of Cambodia (RRC) were underpaid, and professional skills and staffing levels were deteriorating. As a result, the railway was operating at a loss. Neither the RRC nor the Government of Cambodia had the resources required to turn the railway around. The Cambodian government initiated the Rehabilitation of the Railway project in 2007 in collaboration with the ADB. Its objective was to restore railway infrastructure by rehabilitating the existing track and re-establishing Cambodia’s rail connection with Thailand. However, both the MPWT and ADB were ineffective in their management of essential aspects of the project’s planning and implementation. As a result, the entire Southern Line to Sihanoukville Port opened in January 2013, which was about 18 months behind schedule. 	Poor condition of equipment and facility and poor management by operator and government.
Indonesia	Saragih (2015)	<ul style="list-style-type: none"> PT Kereta Api Indonesia (KAI), which was regarded as a very low-performance state-owned railway company in Indonesia until 2009, under Ignatius Jonan's leadership experienced a very significant improvement in performance. Quality of the infrastructure continued to decline; the facilities had passed the limit age of service; number of locomotives, freight cars and trains circuits decreased; quality of service was low; there were back-logs, security and passenger safety was not guaranteed. Company was in the category of BBB (less healthy condition) 	Poor condition of equipment and facility.
	Djuraid (2013)	<ul style="list-style-type: none"> Before Jonan led in 2009, KAI suffered a loss of IDR 38.6 billion in 2007, and increased further to hit IDR 82.6 billion in 2008. The challenges arising when Jonan appointed KAI to revitalize were not only from these hard aspects, but also from the soft aspects that were low discipline and self - oriented workers rather than customer - oriented, weak implementation of good corporate governance, and lack of visionary leadership 	Poor management and weak implementation.

Malaysia	N. Hafiza <i>et al</i> (2013)	<ul style="list-style-type: none"> Although Malaysia already has its own rail transportation system, most of the systems are limited only around the Selangor and Kuala Lumpur area 	Poor robustness and interconnectivity.
	S. Starcey (2003)	<ul style="list-style-type: none"> Ridership was low representing only about 20% of total passenger travel in Kuala Lumpur compared to cities in neighbouring countries, ranging from at least 40% to over 70%. The lack of integration and thus poor accessibility and service reliability is one possible cause of the low ridership. Many people would prefer to drive, rather than take public transport. Due to a combination of low ridership and competition between suppliers, many of the transport companies faced serious financial difficulties for several years 	Lack of integration and poor accessibility.
Myanmar	The Republic of the Union of Myanmar (2017)	<ul style="list-style-type: none"> The Republic of the Union of Myanmar Railways reported that with regard to their railway infrastructure, existing railway lines are deteriorating as a result of aging, causing frequent problems such as train delays and accidents, including derailment and train separation. 	Poor condition of equipment and facility.
Philippines	C. Elemia (2019)	<ul style="list-style-type: none"> Philippine National Railways (PNR) is the main issue with Philippine's Railway System. Many passengers have to bear long lines, dilapidated stations, grumpy train staff and the stress caused by unreliable trains and timetables. The railway schedules are seldom observed, the journeys are delayed and the trains often break down. Even if the situation is really bad, passengers still have no choice but to use the PNR because it is the fastest way to avoid traffic. Data showed that only 15 train sets were available in January and 13 train sets were available in February to serve tens of thousands of passengers daily. The number of passengers per train is not limited, with Garduque, Garcia and Villa claiming trains are always crowded. 	Poor management.
Singapore	Asean Today (2017)	<ul style="list-style-type: none"> Trains reached a delay of more than five minutes, still lag behind other top-notch modern cities but not inherently a failure. A decrease from 0.33 delays per 100,000 car-km in 2013 to 0.12 in 2016. Despite those promising figures, the overall transport performance in Singapore is still lagging behind due to the number of significant delays. Five major disturbances surpassed or equalled 30 minutes in 2014, and nine in 2016. 	Poor management.
Thailand	Bangkok Post (2012)	<ul style="list-style-type: none"> The SRT has long been perceived by the public as inefficient and resistant to change. Trains are usually late, and the majority of their machinery is old and poorly maintained. The SRT, the worst financially performing state enterprise, operates consistently at a loss despite being invested with large amounts of property and obtaining large government budgets; in 2010, it posted a preliminary loss of 7.58 billion bah 	Poor management, poor condition of equipment and facility.
	Bangkok Post (2010), Asia Sentinel (2012)	<ul style="list-style-type: none"> Recurring efforts by the government to restructure and/or privatize the Union throughout the 2000s have always been strongly opposed and have made no progress. 	Political issue.
	Bangkok Post (2018)	<ul style="list-style-type: none"> The poor financial performance and opposition to reform of the SRT, combined with the 1997 Asian financial crisis, culminating in the imposing of strict restrictions on SRT staff. The SRT employs about 4,000 daily workers to make up the shortfall, normally at daily wages of 300 baht. It has also forced the SRT to pay the current employees massive amounts of overtime pay. 	Poor financial performance.
	Bangkok Post (2019)	<ul style="list-style-type: none"> The SRT Board approved the recruitment of 1,330 new employees to bring the workforce to 15,660, which is still less than required to resolve staff shortages. 	Poor management.

	Bangkok Post (2017), Thai PBS (2017)	<ul style="list-style-type: none"> SRT also faces management issues. In February 2017, Prime Minister Prayut Chan-o-cha dismissed the governor and board of the State Railway of Thailand using his special powers under Section 44 of the provisional constitution to resolve a long list of complaints accusing SRT of lack of transparency in bids for projects and procurement deals. 	Poor management and poor financial performance.
Vietnam	Muabanoto (2011)	<ul style="list-style-type: none"> While the condition of the road network in the country is continually improving, train accidents still happen in Vietnam. In 2010 there were 451 rail accidents reported across the country's railway network, resulting in 211 deaths and 284 injuries. 	Poor equipment and facility.
	Japan International Cooperation Agency (2007)	<ul style="list-style-type: none"> A joint Japanese-Vietnamese evaluation team reported that the poor state of the railway infrastructure was the main cause of most rail accidents, the most common of which were train crashes against vehicles and passengers, especially at illegal crossings 	Poor equipment and facility.
	VietnamNet (2010), Vietnam News Service (2011)	<ul style="list-style-type: none"> As of 2010, about 90% of all rail accidents occurred at level crossings without safety fencing and most were apparently caused by motorists who did not comply with traffic safety laws. 	Low act in accordance by citizens.

Table 2: Three-point scale risk scale by Delphi Technique (JISC 2014)

Scale	Probability	Impact
Low	May occur occasionally	Minor impact on time, cost and quality
Medium	Is as like as not to occur	Substantial impact on time, cost and quality
High	Is almost certain to occur	Substantial impact on time, cost and quality

4.0 RESULTS

This subtopic presents the trend analysis extracted from the data collected for each country in the Southeast Asian region from the year 2000 until 2020. The trend analysis involves train accidents and incidents over a 20-year time frame.

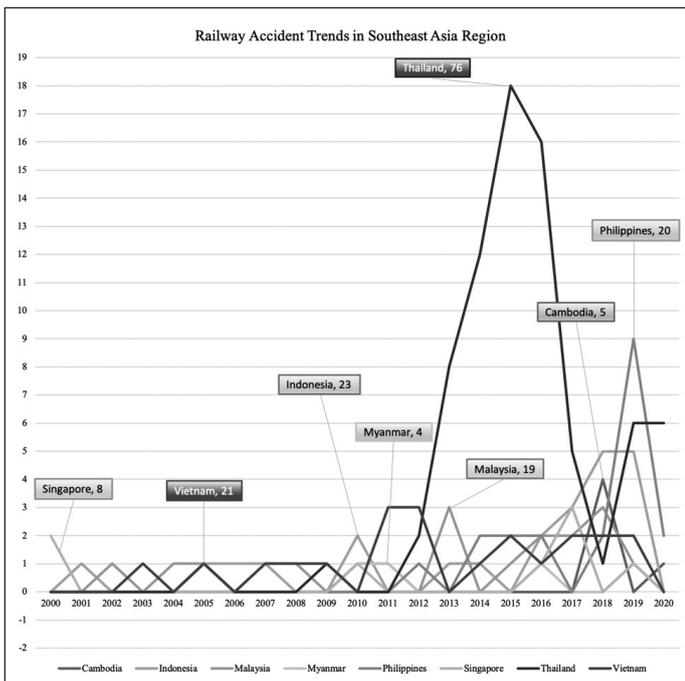


Figure 3a: Rail Accidents Trends of Countries in Southeast Asia Region

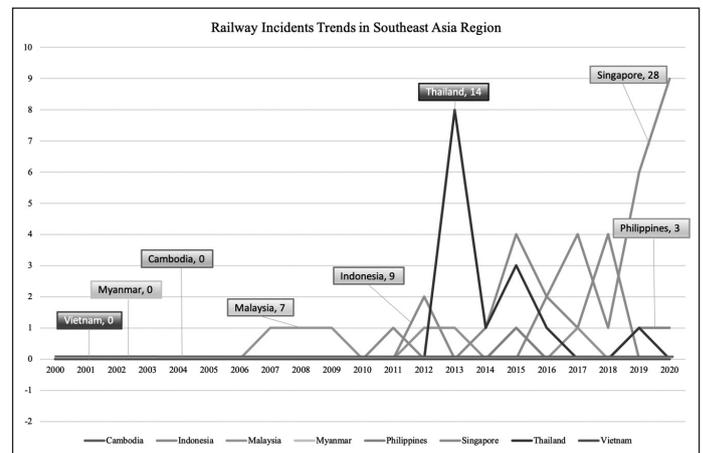


Figure 3b: Rail Incidents Trends of Countries in Southeast Asia Region

4.1.1 Cambodia

The trend analysis for Cambodia’s rail accident and incident for the past 20 years is shown in Figures 3a and 3b. From the trend analysis graph, it evidently shows that there are a number or rail accidents reported but no rail incidents. The total reported rail accidents in Cambodia is five (5) cases. The rail accidents started to occur in the year 2018 with four (4) cases in a year and fluctuated drastically in 2019 with no reported cases. However in the first quarter of 2020, one (1) case was reported.

The robustness of Cambodia’s railway network is undetected as the only existing railway line is from Sihanoukville to Poipet, so the robustness for Cambodia is considered low. The severity of the rail accidents can be concluded as low but every cases

reported are fatal-prone which shows that every rail accidents happened in Cambodia are low risk.

4.1.2 Indonesia

The trend analysis for Indonesia's rail accident and incident for the past 20 years is shown in Figures 3a and 3b. From the trend analysis graph, it evidently shows that there are a number of rail accidents and incidents reported. The total reported rail incidents in Indonesia is nine (9) cases while for rail accidents is 23 cases.

The total number of reported cases for Indonesia is 32 case which is considered as medium. The fatality number is 137 casualties and 434 injuries from these rail accidents which is terribly high from just 32 cases. The most tragic accident was reported in 2005 where a collision happened at Bandar Lampung and have caused seven (7) deaths and 200 injuries. The severity of the rail accidents shows that every rail accidents happened in Indonesia are high-risk.

The robustness of Indonesia's railway network is high as it covers almost all the parts in Indonesia. However, fatality number shows otherwise. This shows that no matter how high the robustness of Indonesia's railway network, every rail accidents that happened are high-risk to the passengers.

4.1.3 Malaysia

The trend analysis for Malaysia's rail accident and incident for the past 20 years is shown in Figures 3a and 3b. From the trend analysis graph, it evidently shows that there are a number of rail accidents and incidents reported. The total reported rail incidents in Malaysia is seven (7) cases while for rail accidents is 19 cases.

The total number of reported cases for Malaysia is 26 case which is considered as medium. The fatality number is 10 casualties and 78 injuries from these rail incidents and accidents which is medium. The most tragic accident was reported in 2004 where a collision happened at Tiroi-Seremban Station, Negeri Sembilan and have caused 40 injured. The severity of the rail incident accidents can be concluded as low for every rail accidents happened in Malaysia.

The robustness of Malaysia's railway network is high as it covers almost all parts of the country. However, the fatality number also shows that the high robustness of Malaysia's railway network has likely increases the railway safety. However, rail accidents and incidents still happen in Malaysia and therefore their risk is low.

4.1.4 Myanmar

The trend analysis for Myanmar's rail accident and incident for the past 20 years is shown in Figures 3a and 3b. From the trend analysis graph, it evidently shows that there are a number of rail accidents reported but no rail incidents. The total reported rail accidents in Myanmar is four (4) cases.

Even the total number of reported cases for Myanmar is low, but all of the cases are categorized as accidents that have caused passengers killed or injured. The fatality number for Cambodia is 34 being killed and 96 got injured from these rail accidents which is terribly high from just four (4) cases. The most tragic accident was reported in 2012 where a collision happened at Kantbalu, Rangoon and this accident alone caused 27 casualties and 80 injuries. The severity of the rail accidents can be concluded as which shows that every rail accidents happened in Myanmar are high-risk.

The robustness of Myanmar's railway network is high as can be seen in the railway network map. According to Andersson (2014), high robustness can be referred as a railway system with high safety level where accidents seldom occur and few people get injured. Although this can be seen from Myanmar's trend analysis, but the fatality number shows otherwise. This shows that no matter how high the robustness of Myanmar's railway network, every rail accidents that happened are high-risk to the passengers.

4.1.5 Philippines

The trend analysis for Philippines's rail accident and incident for the past 20 years is shown in Figures 3a and 3b. From the trend analysis graph, it evidently shows that there are a number of rail accidents and incidents reported. The total reported rail incidents in Philippines is three (3) cases while for rail accidents is 20 cases.

The total number of reported cases for Philippines is 23 case which is considered as medium. The fatality number is eight (8) being killed and 72 got injured from these rail incidents and accidents which is medium. There are no tragic accidents that involved a lot of lives but the most tragic accident to date until now happened in 2019 where a power trip caused rectifier substations located between Anonas and Katipunan stations and in the Santolan depot to catch fire and cutting the line's power supply in the area (Yahoo Philippines News 2019). Although there were no fatalities from the reported event, it is still considered an accident as it involved the damage of the trains, facility and the system itself. Therefore, the severity of the rail incident accidents can be concluded as low for every rail accidents happened in Philippines.

The robustness of Philippines's railway network is medium as it can only be seen in the Manila area where it is the capital city of Philippines. Railway lines that are likely to cover the whole country are still under construction. However, the fatality number also shows that the high robustness of Philippines's railway network has put a positive effect on the country's railway safety. However, rail accidents and incidents still happen in Philippines and therefore their risk is low.

4.1.6 Singapore

The trend analysis for Singapore's rail accident and incident for the past 20 years is shown in Figures 3a and 3b. From the trend analysis graph, it evidently shows that there are a number of rail accidents and incidents reported. The total reported rail incidents in Singapore is 28 cases while for rail accidents is eight (8) cases. Singapore is the only country in the Southeast region that the total number of rail incidents exceeded the total number of rail accidents.

The total number of reported cases for Singapore is 36 case which is considered as medium. Nevertheless, the fatality number is low with five (5) killed and 43 injured to be compared with the total number of reported cases in Singapore. So far the only tragic accident in Singapore is a collision in 2017 at Joo Koon MRT Station that caused 38 passengers to be injured but no passengers were killed (Strait Times 2017). Therefore, the severity of the rail incident accidents can be concluded as low for every rail accidents happened in Singapore.

The robustness of Singapore's railway network is high as it covers almost all parts of the country. Hence, the theory

developed by Andersson (2014) where high robustness in a railway system equates to high safety level is proven through Singapore’s fatality number. Therefore, the risk of railway system in Singapore is low.

4.1.7 Thailand

The trend analysis for Thailand’s rail accident and incident for the past 20 years is shown in Figures 3a and 3b. From the trend analysis graph, it evidently shows that there are a number of rail accidents and incidents reported. The total reported rail incidents in Thailand is 14 cases while for rail accidents is 76 cases.

The total number of reported cases for Thailand is 90 case which is the highest among other countries in Southeast Asian region. The fatality numbers are 87 casualties and 484 injuries which is outrageously high too. Almost every week there will be rail accidents or incident reported in Thailand news to the point that the reporters came out with the headline, “Another day, another train-car collision” (Bangkok Post 2014). Therefore, the severity of the rail incident accidents in Thailand can be concluded as high.

The robustness of Thailand’s railway network is high as all parts of the country are covered with railway lines. However, as seen from Thailand’s trend analysis and the fatality number,

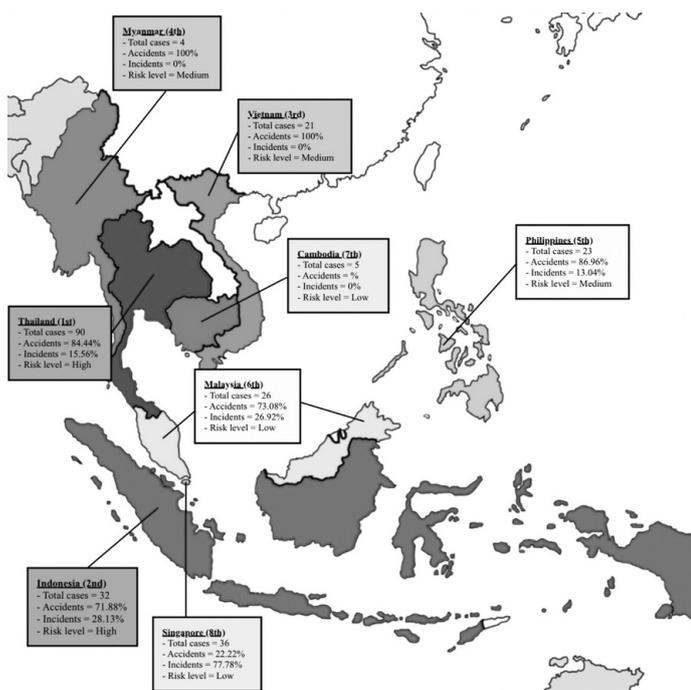


Figure 10: Ranked railway safety map

this proves otherwise. The high robustness of Thailand’s railway network does not promise the safety of their railway system, hence, every rail accidents and incidents that happened are high-risk to the passengers.

4.1.8 Vietnam

The trend analysis for Vietnam’s rail accident and incident for the past 20 years is shown in Figures 3a and 3b. From the trend analysis graph, it evidently shows that there are a number of rail accidents reported but no rail incidents. The total reported rail accidents in Myanmar is 21 cases.

The robustness of Vietnam’s railway network can only be seen at the Hanoi area which is the uptown area of Vietnam. Even though there are three (3) train services with medium to high fatality number in Vietnam, but every rail accident that happened have caused at least one (1) passenger to be killed. The severity of the rail accidents can be concluded as which shows that every rail accidents happened in Myanmar are medium risky.

4.2 Summary of Results

Table 3 presents the summary of results of trend analysis of countries in Southeast Asian region with computation of ratio of killed, ratio of injured, ratio of total number of accidents and ratio of total number of incidents. Lastly, the railway safety for every country is ranked from the most risky railway system to the least risky railway system.

5.0 DISCUSSION

To get a clearer picture from Table 3, a ranked railway safety map is created solely made to show from the most risky railway system to the least risky railway system.

To justify the railway safety rank in the last column in Table 3, the ranks are based on the AHP designed by the researchers themselves by taking account five criteria which are; number of accident and incident, fatality number, level of robustness, level of risk and ratio of killed and injured.

Taking the most risky country, Thailand is ranked first in the risk rank. Not only the case in Thailand are high, but the fatality number is high too. The percentage of rail accident itself is 84.44, so it can be concluded that every rail trip in the future, it possess high risk to their passengers. Level of robustness can only be determined by looking closely at the railway network. According to Andersson (2014), high robustness equates to high safety in railway system but the cases in Thailand proves the theory otherwise.

Table 3: Summary results of trend analysis of countries in Southeast Asian region

Country	Level of Robustness	Level of Risk	Ratio of Killed (%)	Ratio of Injured (%)	Ratio of Total Number of Accidents (%)	Ratio of Total Number of Incidents (%)	Railway Safety Rank
Cambodia	Low	Low	50	50	100	0	7
Indonesia	High	High	23.99	76.01	71.88	28.13	2
Malaysia	High	Low	11.36	88.64	73.08	26.92	6
Myanmar	High	Medium	26.15	73.85	100	0	4
Philippines	Medium	Low	10	90	86.96	13.04	5
Singapore	High	Low	10.42	89.58	22.22	77.78	8
Thailand	High	High	15.24	84.76	84.44	15.56	1
Vietnam	Medium	Medium	23.04	76.96	100	0	3

While for the least risky railway system in Southeast Asia, it is Singapore. Singapore is the only country that has the highest rail incidents with 77.78% of the data. Rail incidents do not cause injury or death so that is partially soothing. However, Singapore tends to face a lot of frustration from the users, not only the station is crowded with enraged users but also a nuisance to the users, operators and facility itself. Nevertheless, that is the only problem that Singapore railway system faces; delays. Since most of the cases are incidents, it is believed that they would be no fatality number. That's why it is concluded that every trip in Singapore in the future is of low risk. Not to mention the robustness of their railway system is astounding. So this proves Andersson's theory.

In terms of which country that has the best and comprehensive data, it would be Thailand. Most of the news for Thailand are gathered from their local news which is The Bangkok Post. Since rail accidents and incidents happens quite often in Thailand, the reporter wrote a detailed news report regarding with the rail accidents and incidents. So it can be stated that the news they published are mostly complete as they publicly announce the type of accident, how did it happen and what are the causes.

When it comes to which country exhibits the best trend, it is without a doubt that Singapore has the best trend. Singapore is the only country in Southeast Asia region that has more incidents than accidents. The researcher's judgement on why it has the best trend is because the trend for rail accident does not surpass the trend for rail incidents.

The country that can be seen here that has the potential to be the best in the region is Singapore. For country that seems to be seen as regressing would be Cambodia since the robustness seen from the map is very low. The only railway line in Cambodia is from Silhanoukville to Poipet. Like in every other countries, their future railway projects would be at least in the planning but there are no plans found for Cambodia's future railway projects.

6.0 CONCLUSION AND RECOMMENDATIONS

The situation of all countries has been studied which produced the trend analysis to identify thoroughly the medium-trend risk of each country. Through the process of performing analysis, robustness assessment of each country's railway system had been done to further determine the risk of each railway system.

This study is expected to be used as a tool or a benchmark for regular rail users, railway operators and policy makers. This is to notify and report to regular rail users to know the risk they face every day when using their countries' rail transportation, railway operators to improve their facility, infrastructure, management and customer service and also policy makers to further understand the issues related to their own railway system.

This study also hopes that railway operators and government authorities will shift their focus and further understand the criticalness of railway safety. Hence, improvements of railway safety with all the issues being addressed is expected for a better experience and safety for the people of each country.

As for recommendations, further study is needed to gather accurate sets of data from each country. These sets of data may be obtained from railway companies or operators so a much more complex statistical approach can be done to further analyse the railway safety in Southeast Asia.

7.0 ACKNOWLEDGEMENTS

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PROFILES



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REVIEW OF FIRE-RELATED ASSESSMENT DAMAGE OF STEEL OFFSHORE STRUCTURES

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ABSTRACT

Fixed offshore structures are continuously exposed to risk of hydrocarbon fire or cellulosic fire. Hydrocarbon fire generally causes more detrimental effect than cellulosic fire because the rapid increment of temperature gives little response time for people to evacuate the location or to put off the fire. Metallography tests have demonstrated that steel structures continuously exposed to temperature escalation from fires will lose their mechanical properties such as yield strength, tensile strength, toughness, hardenability and elastic modulus. Thus, to understand the structural response during fire, structural integrity assessment with revised steel mechanical properties is advised to be performed. The outcome of the analysis helps to identify the hotspots of the steel structures due to the fire and allow the investigation team to further perform detailed inspection and proposed structural repair to reinstate the integrity of the steel structures. This introductory paper reviews a procedure to appraise structures after a fire incident with the objective of filling the gap of the absence of standard assessment procedure. The procedure is based on experience encounters and proposals of practising engineers and utilizes basic engineering mechanics and materials science. The procedure is not a standard operating procedure but should be employed by engineers to emphasise and reiterate the need of a rigid standard.

Keywords: Fixed Offshore Structures, Hydrocarbon Fire, Hotspots, Metallography Tests, Structural Integrity Assessment

1.0 INTRODUCTION

Fixed offshore structures are designed to accommodate rotating equipment, heaters, pressurized vessels, pipelines, electrical and instrument facilities which operate continuously except during maintenance and shutdowns. The structures are in constant threat to fire hazards because the basic elements to initiate fire, such as oxygen, fuel and heat, are highly present. Fires have high potential to cause major damage to offshore facilities and affect the structural integrity of the fixed offshore platform, globally or locally. The intensity of the fire on offshore facilities depends on the quantity, type and rate of release of combustible materials from the source. Some examples of major hydrocarbon fire incidents in the history of oil and gas industry, see Figures 1, are the 1988 Alpha Piper fire disaster [1], 2005 Mumbai High fire incident [2] and 2010 Deepwater Horizon fire incident [3] which caused a few hundred fatalities as well as environmental and asset damages and losses. These incidents led to the industry having a review at their fire related hazard management, competency of people managing and operating offshore facilities, safety rules and regulation, emergency and evacuation requirements, equipment layout and protection system of offshore facilities.

Offshore facilities are equipped with fire and gas detection system, isolation system, active fire protection system and passive fire protection system. The main function of fire protection system is to prevent or delay the escalation of fire so that onboard personnel can escape and evacuate the platform in due time. Examples of active fire protection system are fire



(a) Piper Alpha Disaster, 1988
(Source: The Maritime Executive, 2018 [1])

(b) Mumbai High North
Fire Incident
(Daley, 2013 [2])



(c) Deepwater Horizon Disaster, 2010
(Source: University of Texas News, 2019 [3])

**Figures 1: Major hydrocarbon fire incidents
in the history of oil and gas industry**

extinguisher and sprinkler/deluge system while passive fire protection system are intumescent coating system and fire resistance/insulation system. Passive fire protection system is only installed on critical safety elements such as living quarters, temporary refuge, instrument rooms, battery rooms, pressurized vessel and others. However, many major structural components of fixed offshore structures such as beams, braces, columns and deck plates are not protected due to “burn-down” design philosophy being adopted. Therefore, they are exposed to damage and loss of integrity under high temperature fire. This introductory paper discusses the effect of fire on offshore steel structures and considerations to be accounted when assessing structural integrity of offshore structures exposed to fire. Further work is being carried out to propose, systemize and routinize a method to assess structural integrity of steel offshore platform in a fire event.

2.0 TYPES OF FIRE

Fire incidents in offshore facilities are categorized into hydrocarbon fire or cellulosic fire. Hydrocarbon fire has higher rate of incidents than cellulosic fire. It achieves peak temperature instantaneously after ignition as demonstrated in Figure 2. The hydrocarbon fire reaches 800°C within a few minutes after ignition (Promat, 2020) [6]. Since hydrocarbon fuel is very flammable, it will spread rapidly, burns fiercely and generates high heat flux. Steel structures exposed to hydrocarbon fire will lose its strength and stiffness rapidly. For example, at 600°C, the yield strength of steel and modulus of elasticity will be reduced to 17.3% and 26.5% of their respective values at ambient temperature (API FB, 2006) [4].

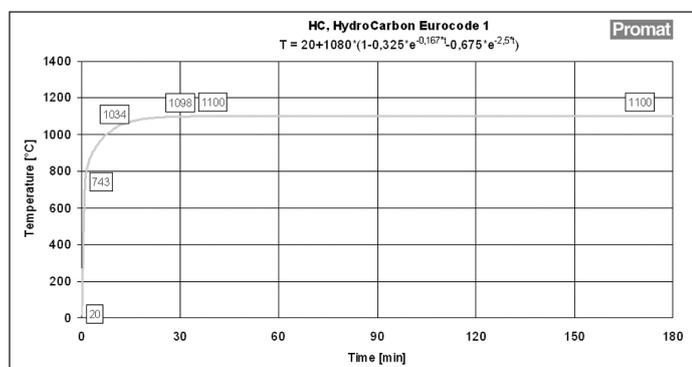


Figure 2: Hydrocarbon fire curve – Temperature vs Time (Promat, 2020) [6]

Cellulosic fire is fuelled by cellulose materials such as timber, paper and cotton. Cellulosic fire relatively grows slower although in some occasion its intensity may ultimately exceed that of hydrocarbon fire. Figure 3 shows the temperature development of cellulosic fire, which demonstrates gradual temperature increment from ignition point. In this example, it takes almost 30 minutes from ignition for the temperature to escalate to 800°C.

In general, hydrocarbon fire is more dangerous than cellulosic fire due to the fact the rapid increment of temperature gives little response time for people to evacuate the location or to put-off the fire. In offshore industry, hydrocarbon fire is more frequently reported because of the continuous presence of hydrocarbon. Due to the threat to people, asset, environment and

business reputation, careful consideration in designing offshore platform is required in order to minimize the escalation effect of fire events.

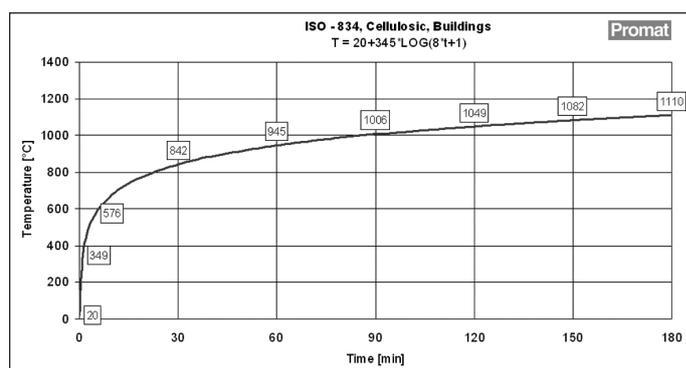


Figure 3: Cellulosic Fire Curve – Temperature vs Time (Promat, 2020) [6]

3.0 STEEL STRUCTURE RESPONSE TO HYDROCARBON FIRE

Worldwide, there are about 6000 fixed offshore platforms installed in water depths ranging from 9.0m to 2100m (Schroeder and Love, 2004) [7]. Fixed offshore platforms are mainly constructed from structural carbon steel because its behaviour is well understood, recyclable and reasonably priced. The mechanical properties of various categories of carbon steel, component shape, cross-section and chemical composition are listed in established standards and codes such as American Institute of Steel Construction (AISC) and American Petroleum Institute (API). An important property of carbon steel is ductility, which allows the redistribution of load in a continuous structural member and at points of high stress concentration. Therefore, carbon steel with high ductility will provide a signal (i.e. substantial distortion) before catastrophic failure. However, when steel structures are exposed to elevated temperatures, in fire or explosion incidents, they rapidly lose strength and stiffness.

The loss of structural yield strength, tensile strength, toughness, hardenability and elastic modulus are due to change in the grain structure of the steel. Other parameters that affect the transformation of carbon steel mechanical properties are phase of metallic structures and elastic-inelastic stress-strain relationship (Villaverde and González, 2012) [8]. Figure 4 shows the comparison on the recommended reduction in yield strength and elastic modulus of carbon steel between codes EN 1993-1-2 and API RP 2FB [4]. The difference between these two design guidelines is that the EN 1993-1-2 [5] is used in the design or reanalysis of onshore building structures exposed to cellulosic fire while API RP 2FB is for offshore structures exposed to hydrocarbon or jet fires. Based on Figure 4, structural steel under cellulosic fire loses its strength at temperature of more than 400°C while for hydrocarbon fire it is as early as 100°C. On the other hand, for stiffness, API RP 2FB recommends the use of gradual reduction in elastic modulus until the temperature reaches 500°C. At temperature of 500°C to 700°C the recommended reduction in the elastic modulus is higher for API RP 2FB than EN 1993-1-2.

Take note, the above procedure is recommended for the design phase of steel structures on shore buildings and offshore facilities or when carrying out structural integrity reanalysis of

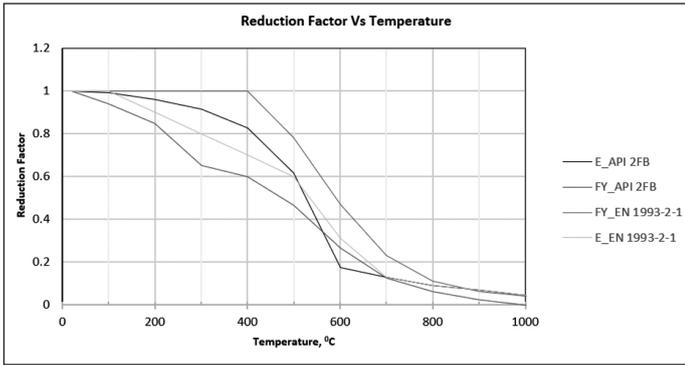


Figure 4: Comparison of yield strength and elastic modulus reduction between EN 1993-2-1 [5] and API RP 2FB [4]

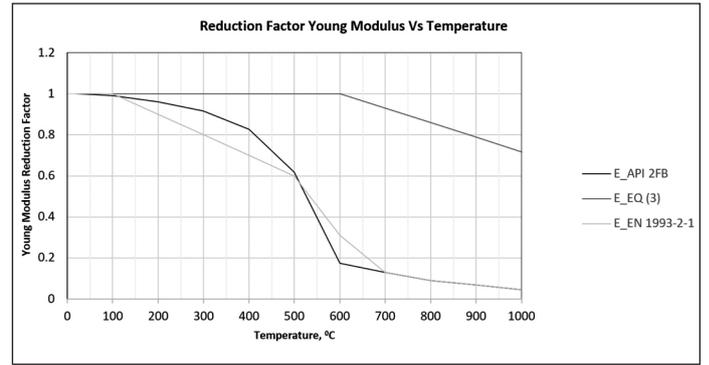


Figure 5: Comparison of elastic modulus reduction factor between EN 1993-2-1 [5], API RP 2FB [4] and predicted post fire property

steel structures exposed to fire where no other information are available. Assessment and studies, such as Tide, 1998, Baetu *et al.*, 2016 [11], Villaverde and González, 2012 [8] and Maraves *et al.*, 2017 [10], highlighted the mechanical properties reduction is lower than those predicted by design guidelines. Findings by researchers were also supported by experimental fire tests on full-scale steel structures which observed insignificant strength reduction after the steel structures were heated up to 500°C (Maraves *et al.*, 2017). Maraves *et al.*, (2017) [10] carried out extensive investigation on wide range of experimental studies done on post fire mechanical properties of mild carbon steel and came out with formulations to estimate the residual factor of the mild steel.

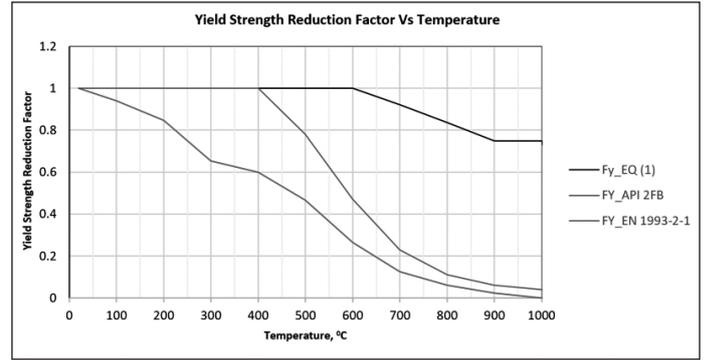


Figure 6: Comparison of yield strength reduction factor between EN 1993-2-1 [5], API RP 2FB [4] and predicted post fire property

$$\frac{f_{yT}}{f_y} = \begin{cases} 1 & T \leq 600^\circ C \\ 1.504 - T/1200 & 600^\circ C < T < 900^\circ C \\ 0.748 & T \geq 900^\circ C \end{cases} \quad (1)$$

$$\frac{f_{uT}}{f_u} = \begin{cases} 1 & T \leq 600^\circ C \\ 1.208 - T/2900 & 600^\circ C < T < 900^\circ C \\ 0.896 & T \geq 900^\circ C \end{cases} \quad (2)$$

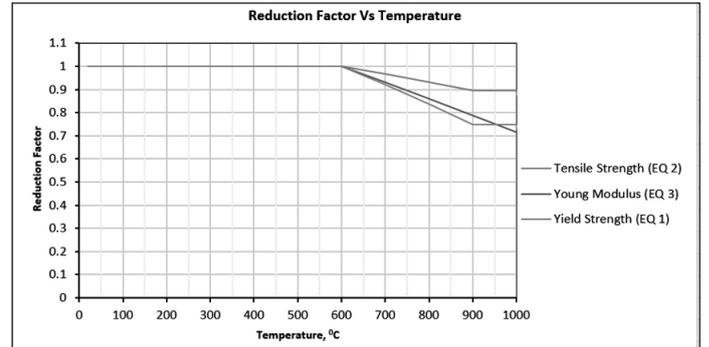


Figure 7: Comparison of reduction factor for post-fire mechanical properties

$$\frac{E_{sT}}{E_s} = \begin{cases} 1 & T \leq 600^\circ C \\ 1.431 - T/1400 & T > 600^\circ C \end{cases} \quad (3)$$

where,

- f_{yT} – yield strength at temperature T, (MPa)
- f_{uT} – tensile strength at temperature T, (MPa)
- E_{sT} – elastic modulus at temperature T, (MPa)
- f_y – yield strength before fire exposure, (MPa)
- f_u – tensile strength before fire exposure, (MPa)
- E_s – tensile strength before fire exposure, (MPa)

Figures 5 and 6 demonstrate that the mechanical properties adopted by design guidelines such as API 2FB and EN 1993-2-1 [5] are much robust or conservative than estimated values in Equations (1) to (3). This clarifies why offshore steel structures, in most cases, show “strong” resistance to hydrocarbon fire.

Figure 7 indicates the post-fire yield strength, elastic modulus and tensile strength of structural steel are not affected by exposure to temperature escalation up to 600°C. For exposure to temperature escalation up to 1000°C, both yield strength and elastic modulus are still maintained at about 75% of intact condition while the tensile strength reduction factor is only about 10% of intact condition. These figures demonstrate that with some repairs or strengthening, steel structures exposed to temperature up to 1000°C will have sufficient strength to continue operation. Based on Figures 5, 6 and 7 it can be concluded that comprehensive evaluation (such as visual inspection, non-destructive test and destructive test) of steel structures in post fire event is very crucial in understanding and determining the mechanical properties of the damaged or affected structure. Information gathered from the post-fire investigation will allow more reliable structural integrity analysis to be done to determine the remaining strength of the structure. The impact of hydrocarbon fire on the overall integrity of the steel structures can

be considered minimum because the structural components still behave elastically because the fire does not change the molecular arrangement of the steel grain structure. On the other hand, steel structures can respond plastically if the total applied stress exceeds the elastic limit of steel. In such case, the steel structure will show visible permanent deformation and continuous loading will cause loss of strength and global collapse of the structure.

Temperature escalation induces thermal stress if free expansion is constrained. This generates compressive loading which may result in buckling. Additionally, uneven temperature profile across member cross section or member with two different thermal expansion properties will generate additional bending on the section (API RP 2FB, 2006). These induced stresses normally govern the structural steel response and failure. Figure 8 shows fire test carried out at Cardington, UK to demonstrate structural failure of steel structure due to stresses induced by thermal effect.



Figure 8: Ductile failure of steel structure due to fire (Bailey et al. [12], 1999; Allam, Burgess and Plank, 1999 [13]).

In addition, buckling of steel structures due to thermal effect induces residual stress to the welded joints. As the buckled beam cools and contracts, the connection material such as weld will be torn apart and causes damage to the welded joints (Tide, 1998) [9] and to bolt connections. Damage to critical welded or bolted joints causes significant reduction to the overall reserve capacity of the steel structures especially structures with minimum redundancy. The structural response due to fire exposure is very much dependent on the type of end restraint of the steel members. For example, structural member with cantilever support has significant room for unrestrained expansion while steel members with restraint at both ends will develop significant compressive stress that can cause buckling.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Offshore facilities are exposed to two types of fire, namely cellulosic fire and hydrocarbon fire. Hydrocarbon fire is more dangerous because of swift temperature escalation and gives little response time for people to evacuate or to stop the fire. Thus, offshore facilities are equipped with fire and gas detection system, isolation system, active fire protection system and passive fire protection system to prevent the escalation of fire or to allow sufficient time for people to escape to safe area.

Metallography tests have always demonstrated that steel structures exposed to elevated temperature, from fire or explosion incidents, may lose their mechanical properties such as yield strength, tensile strength and modulus of elasticity. These mechanical properties can be determined through in-situ non-destructive tests or destructive test via laboratory test

on steel structural components sample extracted from the steel structures exposed to the fire. To simulate and understand the structural steel response during the fire, structural integrity assessment with revised mechanical properties is performed on the steel structures. Additional stress induced by thermal expansion properties of the steel also needs to be considered in the structural integrity assessment of the steel structures exposed to temperature escalation. The outcome of the analysis will identify the hotspot areas of the steel structures due to the fire and allow the structural engineer or site investigation team to further perform detailed inspection and proposed structural repair to reinstate the integrity of the steel structures. ■

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REVIEW OF FIRE-RELATED ASSESSMENT DAMAGE OF STEEL OFFSHORE STRUCTURES

www.maraveas.gr/media/80679/post-fire-assessment-and-reinstatement-of-steel-structures.pdf

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PROFILES



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TEACHING PEDAGOGY FOR ENGINEERING EDUCATION

(Date received: 05.10.2022/Date accepted: 10.02.2023)

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ABSTRACT

In this paper, the teaching philosophies for electrical and electronics engineering education are presented. Being academics in the tertiary institutions emphasis should be placed in the education of knowledge, the constant enhancement of personal knowledge via life-long learning, and the expansion of existing knowledge. In order to mediate an effective teaching and learning process, the implementation of the principle of parsimony in educating the students should be advocated. Since everyone is unique in his/her own way, an educator should also treat the students impartially and sincerely. Different teaching approaches which were developed from the basis of these philosophies have been proposed. The approaches include keeping the explanations simple, predicting the questions and answers, ensuring that the teaching flow is managed in a gradual, systematic, and progressive manner, introducing metaphors, similes, and analogies to assist the pace of learning, using graphical and/or video illustrations, as well as, organizing site visits. The importance of cultivating interests among students should also be stressed. This can be achieved by constantly engaging with the students, keeping the atmosphere collegial, sharing personal real-life experience, incorporating fun activities in the classes, and encouraging students to transcend beyond the requirements set by the educators. It is also worthwhile noting that, the teaching approaches are to be periodically reviewed for continuous improvements.

Keywords: Education, Impartial and sincere education, Knowledge enhancement, Knowledge expansion, Principle of parsimony

1.0 INTRODUCTION

Teaching and learning are a duplex process. While conveying knowledge to the students, with or without an educator realizing it, he/she is learning from them as well. An educator can easily learn from the students how receptive they are with his/her teaching method by scrutinizing the students' behaviour and, sometimes, via their direct feedback. At times, a cosy teaching and learning environment is also conducive for knowledge sharing. Students tend to interact actively with the educators when the atmosphere is suffused with a sense of belonging. This does not only foster the teacher and learners' relationship; it also provides an avenue for knowledge transfer between both parties.

The generations are changing, and, in fact, they are evolving fast. Some of these changes are subtle, while some are conspicuous. Because of this reason, an educator must be particularly meticulous when observing the behaviour of the students (i.e., their gestures, facial expression, cognitive skill, etc.). To ensure an effective process for knowledge transfer, constant attempts to modify the teaching methods to synchronize with the pace of this evolution is necessary. Being able to cope and adapt to the capricious environment certainly, and most definitely, enhances the efficacy of knowledge discovery and propagation.

The study conducted by Choudhury (2019) suggested that a more interactive approach should be implemented to improve the quality of engineering education. In order to enhance the efficacy of knowledge assimilation in engineering education, Hernández-de-Menéndez *et al.* (2019) have proposed adopting a student-centered-learning approach, known as Active Learning.

Similarly, Muradilloevich *et al.* (2020), Nancy *et al.* (2020), Almetov *et al.* (2020), and Lanzo *et al.* (2020) advocate using innovative approaches, such as modelling programs, smart gadgets, and virtual environments to improve the teaching process. In 2014, Metropolia University of Applied Sciences reformed its curriculum into multidisciplinary courses implemented by teacher teams (Vesikivi *et al.*, 2018). The purpose of doing so was to inculcate engineering graduates with the necessary skills. It can be seen from the literature that, the ultimate objective for implementing these different types of approaches is to enhance the effectiveness of education in the engineering discipline. The conveyance of knowledge in engineering education is clearly important because it helps to equip graduates with the necessary survival skill sets in workplaces (Yee and Ho, 2015).

This paper presents the philosophies that has been guiding the author throughout close to 18 years of his teaching career. The teaching methods which are developed based on these philosophies have been implemented to impart knowledge to the students in the engineering field.

2.0 TEACHING PHILOSOPHIES

An educator is perceived as a beacon to illuminate those who wish to learn – in particular, the younger generations. The obligation of teaching is not solely restricted to the task of knowledge transfer. It is a complicated and continuous process which also involves the assimilation of knowledge from different sources and the discovery of new knowledge for the improvement of the society and mankind. In a nutshell, the teaching philosophy proposed

here encompasses education (i.e., to educate the learners), enhancement (i.e., to enhance our own store of knowledge), and expansion (i.e., to expand existing knowledge).

It is also worthwhile noting that, knowledge transmission must also be based on the basis of simplicity. An educator who knows his field well should be able to express himself clearly using the simplest possible and most fundamental method of explanation. He or she should also teach sincerely and impartially.

2.1 The EEE Philosophy

As mentioned in the preceding section, the essence of teaching can be summarized using the EEE philosophy – in which, the three 'E's represent 'Education', 'Enhancement', and 'Expansion'.

Many may view education as a mere process of regurgitating knowledge from reading materials and passing it down to the students. When one delves further into this career, however, one may have the epiphany that it is far more than what it seems to be initially. Apart from the technical skills and knowledge that an educator possesses and wishes to convey, education also involves reaching out to the students and sharing with them the thoughts and behaviour, the beliefs that an educator holds firmly to, and the principles that govern an educator's life. These are the attributes which help to shape the personalities of the students. In other words, an educator's own personal conduct is equally important as the knowledge that he or she possesses. Very often, the teacher is the person whom the students look up to. To the students, their teachers are always their quintessence of virtue. Hence, it is imperative for the educators to constantly remind themselves to uphold and maintain academic and professional morality and integrity.

Educators should also be aware that the teaching and learning process is constantly vibrant. The world is not stagnant, neither is knowledge. Both are growing rapidly over time. To share bleeding edge information to the students, educators have to equip themselves from time to time with the latest know-how. This is especially true for educators involved in teaching courses related to engineering programmes, such as the electrical and electronic engineering. The electrical and electronic industries are developing in leaps and bounds. Today, we are in the cusp of the fourth industrial revolution (IR 4.0), where microchips are operating in the nanometers regime and signals are traveling at the submillimeter wavelengths – the telecommunication technology is now progressing towards its fifth generation (5G). It is the obligation of educators to ensure that the information that is disseminated to the students is contemporary, if not precocious. Hence, educators are required to develop their professional knowledge consistently and persistently in this field.

An educator should also play a part in contributing to the existing store of knowledge. As a researchers, as well as educators in a tertiary institutions, it is incumbent upon educators to seek for novel discoveries in science, technology, engineering, and mathematics (STEM). Excavating new knowledge and sharing it with the community help to expand the horizon of the society and propel the nation to stride forward.

All in all, an effective teaching process usually requires these three elements to be intertwined seamlessly. Educators have to consistently explore new knowledge – discovered either by themselves or others and educate the students with the knowledge that they possess.

2.2 The Principle of Parsimony

The principle of parsimony, or better known as the Ockham's razor (Sober, 1981), advocates one to seek the simplest explanation for a phenomenon (Lazar, 2010). This is to say that a phenomenon should be explained based on the least assumptions and using the simplest form and, yet the explanation is able to convincingly support the manifestations found. Although this principle is commonly implemented in scientific research, it is equally valid in the light of teaching and learning. An educator who is proficient enough in his/her own field should be able to find an easy-to-understand and appropriate method to explain to the students the subjects which are of intricate depth. One should resort to the method of explanation, which is simple but sufficiently accurate, so that even a novice could have the least difficulty in grasping the gist of the subjects. As a matter of fact, a good educator should avoid using terminologies that are so complicated that only aficionados could comprehend, since this will hamper the channel of knowledge propagation. This is especially true when the educator is teaching a group of students, with every one of them having different levels of knowledge absorbing capabilities.

2.3 Impartial and Sincere Education

There is no doubt that one must own various traits to become a successful educator. The febrile passion in teaching, possessing a magnetic personality, effective communication skill, empathy, etc, for instance, are probably some of these traits. However, to teach all students wholeheartedly and to treat every one of them equitably is certainly something an educator could not do without.

To be fair to the students does not mean that the educator has to sacrifice the same amount of time and effort for all students. Each student is unique in his/her own way. Hence, an educator must know how to optimize their strengths and improve their weaknesses. This is to say that each one of them who needs help deserves different amount of attention from the educators. Very often, educators may come across students who are slower in picking up certain subjects in comparison to others. Also, some students may find themselves struggling in adapting to a foreign environment; while others have little difficulty to do so. Hence, to be fair to all students is to ensure that all of them are able to cope well at the end of the day. Educators are supposed to provide tutelage to those who require the need, without discrimination and prejudice and of course, with patience and sincerity too.

3.0 STRATEGY IN TEACHING AND LEARNING

To put it in simple words, teaching and learning is nothing more than the mere process of transmitting and receiving information. To cultivate an effective teaching and learning environment, adopting the correct teaching approaches is of foremost importance. One may have to identify and learn a variety of teaching methods and apply them based on the necessary situations. The key objective of doing so is to ensure that majority, if not all, of the students are able to receive the information that an educator intends to convey. Different classes and different cohorts may exhibit different demographic characteristics. Hence, an approach which works well for a particular group of students may fail when applied to another group. This also means

that, educators should always stay vigilant when conducting their teaching duties. While teaching, educators also need to observe the students to assess their “absorption” rate. Choosing the right approach not only allows the students to learn effectively, it also instills certain tinge of motivation in the students.

3.1 Teaching Approaches

When teaching the students, a simple and direct approach is to be adopted. Keeping the explanation simple and straight forward is an art which may sometimes be challenging to master. When a theorem is inherently complex or an equation is mathematically involved, then one may have to spend quite some effort to gather a way to describe it in its simplest sense. It is essential for educators to make sure that the essence of the theorem or equation is unaltered when describing it using simple and fundamental language. To be able to do so usually requires a profound understanding of the subjects that the educators are teaching.

Educators also have to predict the questions that the students may ask and the answers that should be provided to them so as to convince them. When preparing for a class, educators should try to put themselves in the students’ shoes. Very often, educators may wish to ask themselves, “What kinds of problems would we face if this subject is totally new to us?”. The words used when describing the same subject may also differ, depending on the grades (i.e., either freshman, sophomore, junior or senior) and the academic results (i.e., the CGPA) of the students. Hence, it is advisable to gauge the students’ level of understanding first before deciding on the exact word or method that is to be used for teaching them.

The teaching process should also be conducted in a gradual, systematic, and progressive manner. At times, an educator needs to be extremely patient when teaching the students – particularly, when some of them are slow learners. When there is a need, metaphors, similes and analogies can be used so as to assist the students’ understanding. Take for example the electromagnetic fields and waves course offered virtually in all the electronic engineering programmes in any universities. Very often, the students face difficulty in visualizing the way waves propagate in transmission lines. As can be seen in Figure 1, when a pair of wires are connected to a voltage source at one end and a load at the other, electromagnetic waves travel between both ends. The propagating signal launched from the source is known as the incident wave and is denoted as V_{0+} ; whereas the signal ricocheted from the load back to the source is known as the reflected wave and is denoted as V_{0-} . Maximum amount of power will only be transferred to the load when the reflected wave vanishes and the condition for this to occur is when the magnitude of the load (Z_L) matches that of the characteristic impedance (Z_0). For an experienced physicist or electrical and electronic engineer, this concept is perhaps reasonably logical to be understood; for a novice who has just begun to embark into the field of electrical or electronic engineering, however, it could be relatively abstruse. In order to assist the students in understanding the underlying principle, the author has drawn the image in Figure 2 and told the students to imagine that there are two dinosaurs, one at each end of the transmission lines. The dinosaur at the source is the mother and that at the load is her pampered child. Every time the mother (i.e., source) feeds her child (i.e., load) with muffins (i.e., V_{0+}), she has to make sure that the size of the muffins (i.e., Z_0) is identical with the size of her

child’s mouth (Z_L); otherwise, a fraction of the muffins (V_{0-}) will be spewed back to her. This analogy helps students to visualize the interaction of waves in transmission lines.

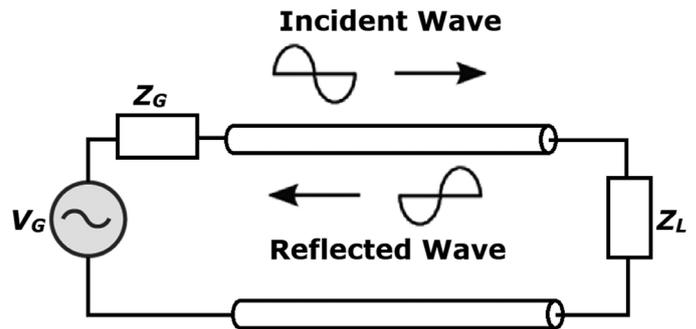


Figure 1: The circuit schematic of a source connected to a load via a coaxial cable (i.e. the transmission line)

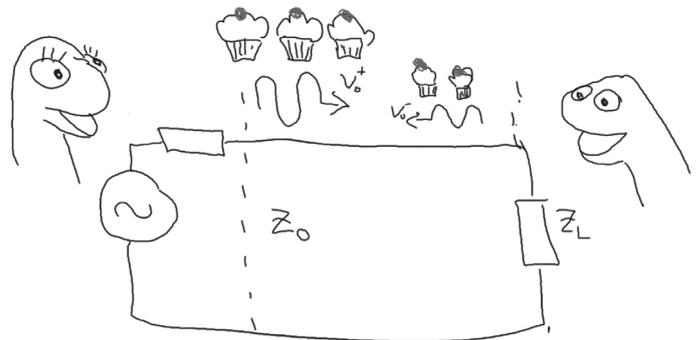


Figure 2: The author used analogy to teach transmission line theory



Figure 3: The students were asked to build solar cars from used aluminum cans for their assignments

Very often, graphical illustrations may become a helpful aid when educators are attempting to explain a subject which could sometimes be abstract to visualize (Yeap, 2020; Yeap *et al.*, 2012). In electrical and electronic engineering, educators often come across subjects which are impalpable – such as, the flow of charges, the propagation of electromagnetic waves and the presence of electric and magnetic fields, to name a few. When it comes to situations where words alone have their limitation for elucidation, educators can resort to using graphics as a teaching aid. Most often than not, a picture is worth a thousand words. Hence, descriptions where words fail, images may come in handy. Graphics usually stay longer in one’s memory than words. Therefore, drawings are also helpful in implanting knowledge and allowing it to stay firmly in the students’

memory. Of course, relying on drawings alone is insufficient. Showing actual real images or videos also help to accelerate the pace of understanding. Take for example, the fabrication process of a microchip. A microchip has to undergo multiple laborious stages before it could finally be taped out. In order to allow the students to appreciate the entire manufacturing process, videos published by chip manufacturers, such as Intel Corporation and Infineon Technologies can be employed for illustrations. This goes without saying that field trips would certainly be of great benefits to the students, since they could witness first-hand the actual manufacturing process which takes place in the factories.

Every now and then, educators should also engage themselves with the students. This is deemed necessary because many students are reticent to the educators. They will only open up to the educators when they start to sense the pastoral care that is extended to them. This helps to develop a sense of belonging in them. Interacting actively with them and using their jargons foster a bond of trust between the educators and the students. Doing so, educators would be able to discover the difficulties that the students face. The author saw changes in students who were initially recalcitrant. They gradually changed their attitude and became more amicable when they sensed the solicitude that is dedicated to them.

Another important aspect that educators have to consider when teaching, is the atmosphere of the class. A cosy and lively atmosphere helps to mediate an effective teaching and learning process too. One way to buoy up the atmosphere, is to tell jokes. Alternatively, educators can also initiate casual conversations with the students occasionally, to ensure that the atmosphere stays collegial.

Although it is delightful to see the students faring well in the subjects that the educators teach them, motivating them to embrace knowledge should preponderate. One should not study solely because one aims to attain good academic results. Such perspective diverts from the genuine objective of learning. Learning should be fun, and a student should learn because he/she is interested to do so. Hence, educators should also nurture the interests of their teachings towards the students. The sense of complacency will certainly imbue the educators when the students start badgering them for more information, with their eyes sparkling with excitement. Sometimes, an educator should also endeavours to give pep talks with words of encouragement. One may be surprised to find that enthusiasms and determinations that build up in the students can form a force to overcome the impediments that they face in the path of learning.

From time to time, educators can also attempt to introduce entertaining and fun activities into the subjects that they teach. Doing so, the students would be able to enjoy themselves while learning. The concept is similar to how parents encouraging toddlers to learn to walk. The skills will be naturally and eternally engraved into one's subconscious when one immersed in the fun process. Needless to say, the pace of learning will certainly be accelerated too. Take for instance the circuit theory course which, again, is a compulsory electronic engineering course in universities. The course describes the relationship of voltage and current and the theorems which govern them. In order to allow the students to relish the gist of the course, the author has asked the students to build solar cars from used aluminium cans, such as those depicted in Figure 3. The students are divided into teams and each team has to design and develop a workable prototype of its own. The farther and easier the car can manoeuvre, the higher

scores the team will obtain. Of course, the ultimate aim of the assignment is to let the students learn how voltage and current generated from the solar panels could be determined. One other advantage of the assignment which is perhaps worthwhile mentioning here is that it inculcates environmental awareness and that the students learn about the importance of recycling wastes.

Cultivating creativity and innovation among the students should also be encouraged. The students should always aim to transcend the expectations set by the educators. Hence, the educators should motivate the students to deliver beyond the basic requirement that are set for them.

4.0 ASSESSMENTS ON TEACHING EFFICACY

Teaching and learning are a duplex activity. This is to say that educators are not supposed to deliver blindly without the initiative to evaluate the students' understanding. The efficacy of teaching could only be verified when educators are able to determine the students' level of understanding, and this could only be achieved via feedbacks from the students. Educators can gauge how receptive the students are to their teaching via interactions with them in the class (i.e., immediate measurements) and assessment of their coursework (i.e., overall measurements).

4.1 Immediate Measurements

Encouraging the students to involve actively in discussions allows educators to receive direct immediate feedbacks from them. Students who are active learners or who have devoted interests in certain subjects will normally volunteer themselves to share their views. An educator could easily tell from his/her discussion with the students how well they have learned the information that the educator intends to impart to them. Immediate corrective actions can then be taken by the educator once he/she is able to identify the students' problems on spot. Some of these corrective actions include giving more examples to the students or trying to use a simpler way to illustrate the same topic. Since a student's memory fades along with time, the problems that the students face may proliferate if clarifications were not provided promptly on spot. It is, however, worthwhile mentioning that not all students are often willing to share their problems. In every class, there is always a handful of which who are shy, quiet and, probably, introvert too. In order to ascertain how well these students in acquiring the knowledge that is delivered to them; educators may have to exploit indirect feedbacks. This can be accomplished via meticulous observation. Scrutinizing their facial expressions and gestures allows educators to gather hints of their level of understanding. Sometimes, educators can also pose questions especially to these groups of students, so as to assess them, and, of course, to also let them know that they have not been neglected.

4.2 Outcome-Based Education

The overall performances of the students are measured via the outcome-based education approach. This approach focuses on empirically measuring the students' performance with respect to a pre-determined set of outcomes (Soh *et al.*, 2010; Yeap *et al.*, 2014). The outcomes outline the attributes the students are expected to know upon the completion of the programme. This

assessment method is currently widely implemented in literally all tertiary institutions in Malaysia. Hence, the coursework and examination questions are prepared in accordance with the outcomes put forth for the course (also known as the course learning outcomes); while these course outcomes are also aligned with the outcomes of the programme (also known as the programme learning outcomes).

There is no doubt that the educators should have certain form of impression on how well the students fare when they first go through the students' works. To be able to assess their works in a fair and systematic manner, however, it should be advisable to prepare rubrics for each coursework. By referring to the rubrics, educators could then grade the students' performance in a rigorous manner. Employing a clear and transparent method to assess the students' coursework is important because it helps the educators to pinpoint the obstacles that are clogging the channel of knowledge propagation – the common errors that most students tend to commit and the topics that many have difficulty grasping. Now, if these problems were identified and solved in time before the end of the semester where the students have to sit for their final examinations, then the educator could, at least, ensure that majority of the students are able to comprehend the essence of the courses, i.e., knowledge which corresponds with the course learning outcomes.

5.0 REVIEW OF TEACHING METHODS

One way to improve an educator's teaching skill is to periodically review both the teaching and assessment methods. It is useful to perform a full and thorough retrospect on the course that the educators have taught upon the completion of it. Since the author has been teaching engineering courses for years, there are some courses that he has been repeatedly teaching. Even so, he still discovers new insights in them every time he performs a thorough review on his delivery and evaluation methods. This is partly because our knowledge and experience grow over time; and partly, also because each individual tends to respond differently in the class. The conglomeration of these factors inspire revelation in us.

In Universiti Tunku Abdul Rahman, a course report is to be prepared at the end of every trimester. The course report records the review of the course. In other words, the educator is to analyze the teaching and assessment methods that he/she has implemented and develops plans for improvement, and all these are to be written down into the report. A course report for the digital integrated circuit designs course taught by the author in every January trimester is shown in Figure 4.

Universiti Tunku Abdul Rahman Form Title: COURSE REPORT Form Number: FM-DGA-001 Rev No: 2 Effective Date: 03/12/2019 Page 1 of 2				Universiti Tunku Abdul Rahman Form Title: COURSE REPORT Form Number: FM-DGA-001 Rev No: 2 Effective Date: 03/12/2019 Page 2 of 2																											
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Figure 4: A sample of the course report

6.0 CONCLUSIONS

In this paper, the author shares the teaching pedagogy that he has developed and clinging to throughout his career in the engineering education. In essence, the author believes that an educator should put emphasis in educating the students, constantly expanding his/her own store of knowledge, and discovering new knowledge for the benefits of mankind. When conveying knowledge to the students, an educator should resort to simple words and a straightforward mean of illustration. Since each student is special in his/her own unique way, an educator should also treat the students equitably and with utmost sincerity. The teaching pedagogy proposed by the author has been incorporated into his teaching methods. These methods have been periodically reviewed to ensure that knowledge could be propagated effectively. ■

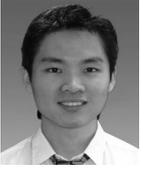
LIST OF NOTATIONS

- EEE is education, enhancement, and expansion
- IR4.0 is the fourth industrial revolution
- STEM is science, technology, engineering, and mathematics
- 5G is the fifth generation
- V_0^+ is the incident wave
- V_0^- is the reflected wave
- Z_0 is the characteristic impedance
- Z_L is the load impedance

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