WHOLE LIFE CARBON EMMISSIONS OF LOW-CARBON HIGH DURABILITY NON-METALLIC BRIDGES

低炭素で耐久性に優れた次世代非鉄製橋梁の生涯炭素排出量

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ゼロセメントコンクリート（STC-ZERO）と非金属補強材のアラミド繊維 FRP ロッド(AFRP)を活用した超高耐久低炭素プレストレストコンクリート橋を開発した。 STC-ZERO は，セメントを一切用いておらず従来のコンクリートに比べて低炭素でありながら，高強度,低収縮, 低クリープといった性能を実現する。 AFRP は，腐食の心配がない。 本技術を適用した AASTHO-PCI BT-72 PC 桁橋とバタフライウェブ橋を設計し, 生涯炭素排出量を算出するとともに，対応する従来の橋と比較した。 その結果，本橋梁を採用することで生涯炭素排出量は約 70% 削減されることが分かった。

キーワード：炭素排出量, ライフサイクルアセスメント（LCA), 非鉄製橋梁, 超高耐久性,
ゼロ-セメントコンクリート（STC-ZERO）

An initiative for ultra-high durability low carbon prestressed concrete bridges utilizing sustainable zero cement concrete (STC-ZERO) and nonmetallic reinforcement is undertaken targeting low carbon sustainable infrastructures. STC-ZERO exhibits high strength, low shrinkage, low creep and low carbon emission compared to the conventional concrete. Aramid fiber PC tendons have no factor of corrosion. Accordingly, an AASTHO-PCI BT-72 PC girder bridge and a butterfly web bridge are designed incorporating this combination and compared with corresponding conventional bridges with respect to whole life carbon emissions. The whole life carbon emissions of next generation non-metallic bridges are expected to be reduced by around 70%.

Key Words: Carbon emission, Life cycle assessment (LCA), Non-metallic bridge, Ultra-high durability, Zero-cement concrete (STC-ZERO)

1. INTRODUCTION

This paper presents a challenging initiative on an ultra-high durability low carbon prestressed concrete next generation bridge utilizing sustainable zero cement concrete (STC-ZERO) and non-metallic reinforcement. CO_2 emission of STC-ZERO is significantly low compared to those of conventional concretes of same strength as cement is entirely replaced[1]. The non-metallic Aramid fiber reinforced polymer (AFRP) PC tendons and glass fiber reinforced polymer (GFRP) reinforcing bars have no factor of deterioration of concrete owing to the nonexistence of corrosion[2]. As STC-ZERO exhibits low pH value, the combination of AFRP and STC-ZERO is practicable. Accordingly, an AASTHO-PCI BT-72 PC composite girder bridge superstructure is designed incorporating this combination and compared with the similar conventional bridge with respect to structural performance and life cycle assessment, specifically equivalent carbon emission in accordance with BS EN15978(2011)[2), 3)]. Additionally, the whole life carbon emission of a single span non-metallic butterfly web bridge incorporating STC-ZERO and AFRP tendons is estimated and compared with the corresponding conventional bridge. Since, there is no repair and rehabilitation requirements, the highly durable BT-72 girder bridge and butterfly web box girder bridge with STC-

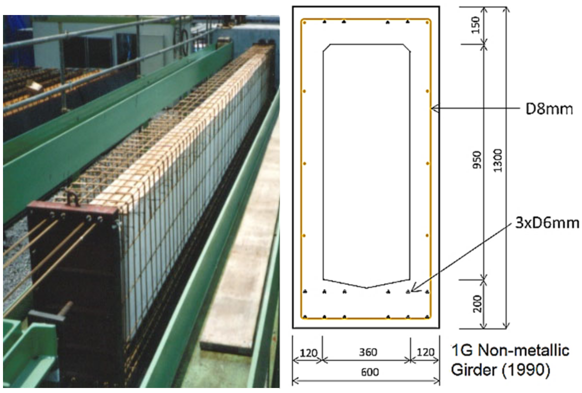

Fig. 1a. 1G non-metallic pre-tensioned girder (1990)

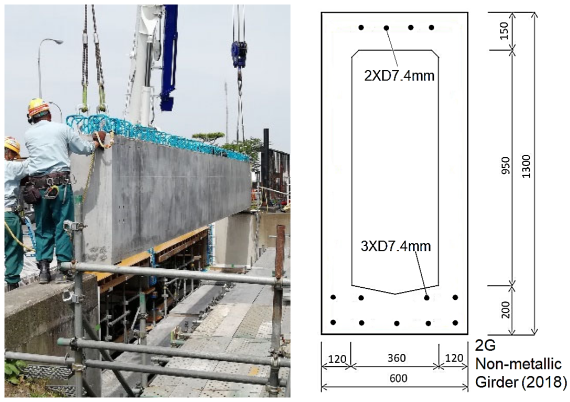

Fig. 1b. 2G non-metallic pre-tensioned girders (2018)

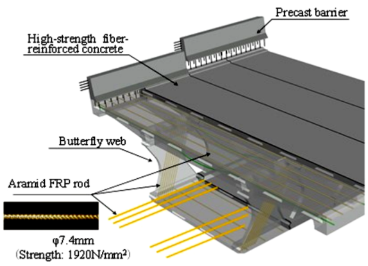

Fig. 2(a). Segment details

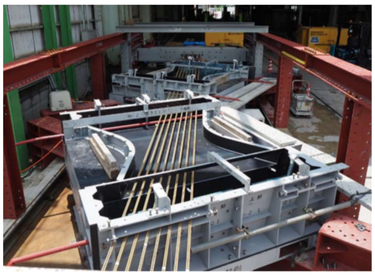

Fig. 2(b). Butterfly web fabrication

Fig. 2(c). Bessodani Bridge

ZERO and non-metallic reinforcement reduces the whole life carbon emission by approximately 70%[2].

2. DEVELOPMENT HISTORY OF NONMETALLIC BRIDGES

The 1st generation (1G) of highly durable non-metallic bridge in Japan was initiated by Sumitomo Mitsui Construction jointly with Teijin Co. Ltd. dates back to 1984. The physical properties of AFRP corresponding to the practical construction requirements i.e., rod handling, heat resistance against welding, physical strength against impact load and concrete casting, relaxation, bond length, strength of bent portion etc. were confirmed and the guidelines for the construction were prepared.[4] In 1990, an innovative pre-tensioned (length=12.5 m) demonstration road bridge was constructed utilizing nonmetallic AFRP tendons (**Fig.1a**) and early strength concrete. Further, in 2018, one of the three pre-tensioned girders from the demonstration road bridge was taken out to confirm its structural performance conducting bending loading test after 28 years of service. The AFRP tendons showed no signs of deterioration and retained the initial strength confirmed through chemical analysis[5]. There was no degradation of bending strength and the performance at the time of construction was maintained up to the test date[6]. Thus, AFRP as a new material applied as prestressing tendons in concrete was confirmed to be intact after more than a quarter century of use.

One of the three pre-tensioned girders constructed in 1990 was replaced by a new girder made of high strength STC-ZERO and AFRP tendons in 2018 (**Fig. 1b**). The new girder was designed with thirteen cables each containing 2× D7.4mm or 3×D7.4mm AFRP deformed rods stressed with 70% of guaranteed strength[5]. There was no transverse shear reinforcement requirement due to the high strength of STC-ZERO incorporating 1vol.% of steel fiber along with the AFRP tendons as bending reinforcement contributing to increased shear strength[5]. Monitoring of the previously constructed two non-metallic girders will also be continued and structural performances will be verified in 2090 after 100 years of construction.

The development of 2nd Generation (2G) non-metallic butterfly web bridge was initiated as joint research with West Nippon Expressway Company (NEXCO West) in Japan in 2010 with the goal of constructing an ultra-high durable corrosion free bridge limiting the cost around 1.5 times of that of a typical concrete bridge[2), 7)]. It is the 26.5m long, 11.55m width with 2.8m girder depth Bessodani Bridge along

Tokushima Expressway commenced in 2020 (**Fig.2a-c**). It is a simply supported bridge with butterfly panels as webs of the box girder constructed as precast segments. The butterfly webs of the girder acting as double Warren truss resulted in a significant reduction of materials[7)]. Shear forces are decomposed into compression and tension forces in the butterfly web panels that successfully eliminates the requirements of shear reinforcement[7)]. Moreover, high-strength fiber reinforced concrete having high tensile and shear strength developed to make members extremely thin, reducing the dead weight of the main girder. AFRP rods were utilized as external post-tensioned cables in the longitudinal direction and pre-tensioned in the transverse direction eliminating steel reinforcement[7)]. This non-metallic bridge is 10% to 20% lighter than conventional structures[7)].

3. FUSION OF NON-METALLIC FRP AND STC-ZERO FOR NEXT GENERATION BRIDGE

The challenging concept of developing ultra-high durability low carbon sustainable prestressed concrete bridges with fusion of innovative zero cement concrete (STC-ZERO) and non-metallic FRP will be discussed in the following sections.

3.1 DEVELOPMENT OF STC-ZERO

The ultra-low shrinkage and high strength sustainable zero cement concrete termed as STC-ZERO is innovated incorporating ferronickel slag sand (FNS), blast furnace slag, fly ash, silica fume and expansive additive allowing ultra-low water to binder ratio[1)]. The compressive strength of STC-ZERO exposed outdoors up to two years with unsealed conditions exceeds 150 MPa since the microstructure continues to be refined through on-going reaction of the remaining supplementary cementitious materials[1), 8)]. Long-term splitting tensile strength of STC-ZERO is higher than that of conventional concrete with identical compressive strength using ordinary Portland cement (OPC) [1)]. Maximum heat of hydration is 30°C-40°C lower than that of conventional concrete of the same strength[1)]. Compressive creep is one-third of that of conventional concrete. Autogenous and drying shrinkage of STC-ZERO is extremely small owing to an internal curing effect contributed by FNS1). Nonetheless, carbon emissions can be reduced by up to 70% compared to normal conventional concrete (NCC)[1)].

3.2 NON-METALLIC REINFORCEMENT REPLACING STEEL

Technora aramid fiber developed by Teijin Limited, which, unlike other aramid fibers, is not affected by alkali[4)]. This property is an absolute requirement for concrete reinforcement materials. AFRP tension material is a continuous aramid fiber bonded in a rod shape with vinyl ester resin[2)]. AFRP rods can be fabricated with nodes, similar to deformed bars greatly enhancing the bond performance and enables concrete embedment with short development lengths[4)]. AFRP tendon exhibits excellent fatigue resistance and equivalent tensile strength as PC steel strands[4)]. Although, the relaxation of AFRP rod is larger than that of conventional PC steel tendon, elastic modulus of AFRP is around one-fourth of steel contributing to low prestress loss due to shrinkage and creep of concrete[9)]. Moreover, corrosion resistant GFRP rods possess good fatigue endurance, low thermal and electrical conductivity, and high longitudinal strength to weight ratio compared to steel reinforcing bars[2)].

3.3 NEXT GENERATION AASHTO-PCI BULB TEE GIRDER BRIDGE

A next generation ASSTHO-PCI BT-72 PC girder bridge superstructure is designed incorporating this revolutionary combination and compared with the similar conventional bridge with respect to structural performance and simplified whole life carbon emissions. A superstructure of typical interior BT-72 PC girder simply supported bridge was designed (**Fig.3a**) in accordance with the AASHTO Load and Resistance Factor Design[2),10)] replacing normal strength concrete with STC-ZERO, steel prestressing strands with AFRP tendons and steel reinforcing bars with GFRP rods. The design specifications of GFRP rods as shear reinforcement of the girder, reinforcement of the composite slab and the traffic barriers are in accordance with AASHTO guidelines[11)]. **Fig.3b** illustrates the reinforcement details of the BT-72 conventional girder and the non-metallic girder of same size. The non-metallic girder is designed with considering four D7.4 mm AFRP rods arranged together as a single tendon unlike the conventional girder. In composite non-metallic RC slab GFRP rods are utilized as primary and distribution reinforcement. Additionally, non-metallic traffic barrier is designed with GFRP rods ensuring sufficient anchor length[2)].

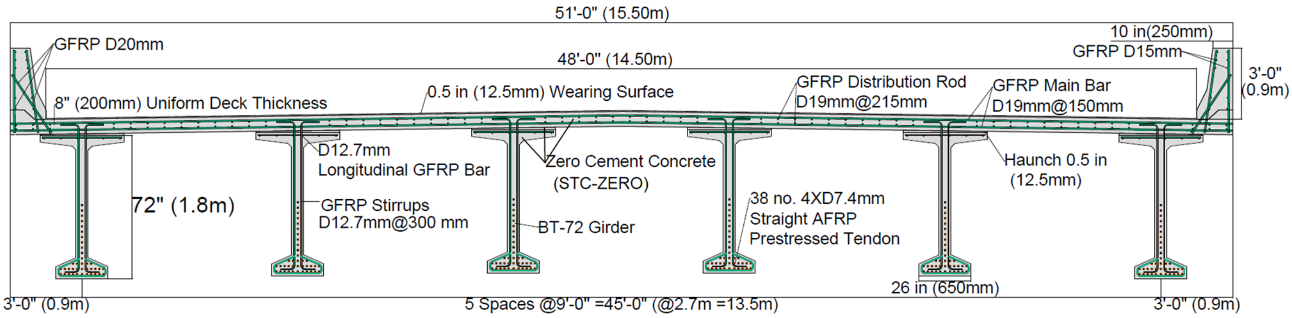

Fig. 3a. Reinforcement details of the next generation BT-72 girder bridge superstructure at mid-span[2)]

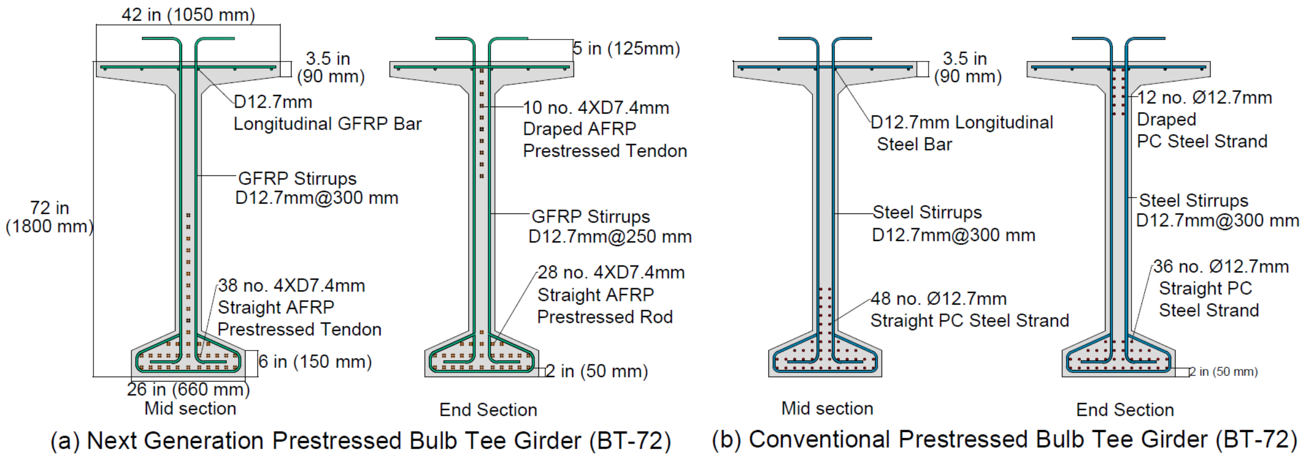

Fig. 3b. Reinforcement details of the next generation and the conventional BT-72 PC girders[2)]

Table 1. Equivalent Carbon Emission in tons (tCO2e) at material production stages (A1-A3)[2)]

Bridge Category	*Sl.no.*	*Item*	*Vol. (m^3)*	*Unit Weight (kg/m^3)*	*Weight (kg)*	*CO_2 Coeficient*		*tCO_2e per material component*	*tCO_2e per bridge element*	*No. of Unit*	*tCO_2e per total elements*	*Tolal tCO2e*	Total Volume (m^3)	tCO_2e/m^3
Conventional BT-72 Girder Bridge	PC Girder	NCC	18.3	2321	42358	356	kg/m^3	6.50	12.8	6	76.7	141	247	0.57
		φ12.7mm Steel PC Strand	0.2	7850	1373	4.03	kg/kg	5.53						
		D12.7mm Steel Bars	0.1	7850	992	0.77	kg/kg	0.76						
	Composite Slab	NCC	116.6	2321	270594	356	kg/m^3	41.50	54.9	1	54.9			
		D16mm Steel Bars	2.2	7850	17420	0.77	kg/kg	13.36						
	Traffic Barrier	NCC	10.6	2321	24510	356	kg/m^3	3.76	4.9	2	9.8			
		D16 & D19mm Steel Bars	0.2	7850	1506	0.77	kg/kg	1.16						
Next Generation BT-72 Girder Bridge	PC Girder	STC-ZERO	18.3	2520	45990	100	kg/m^3	1.83	5.4	6	32.1	70	247	0.28
		D7.4mm AFRP PC Tendon	0.2	1300	308	9.10	kg/kg	2.80						
		D12.7mm GFRP Rod	0.1	1740	235	3.09	kg/kg	0.73						
	Composite Slab	STC-ZERO	116.6	2520	293794	100	kg/m^3	11.66	32.7	1.0	32.7			
		19mm GFRP Rods	3.2	2100	6814	3.09	kg/kg	21.06						
	Traffic Barrier	STC-ZERO	10.6	2520	26611	100	kg/m^3	1.06	2.67	2.0	5.3			
		D15 GFRP mm bars	0.03	2000	65	3.09	kg/kg	0.20						
		D20 GFRP mm bars	0.2	2675	458	3.09	kg/kg	1.42						

Table 2. Probabilistic estimation of whole life tCO2e of the BT-72 girder bridge superstructure[2)]

Bridge category	*Lifecycle factor*	*tCO_2e*					*Whole life emission rate tCO_2e/m^3*	*tCO_2e reduction (%)*
		Modue A		*Module B and C*		*Whole life Emission (A+B+C)*		
		A1-A3 (80% of A)	*A4-A5 (20% of A)*					
Conventional Bridge	Repair & Replacement	141	35	265	(1.5 times of A)	442	1.8	NA
Next Generation Bridge	No Repair & Replacement	70	18	12	(12% of whole life emission)	100	0.4	77

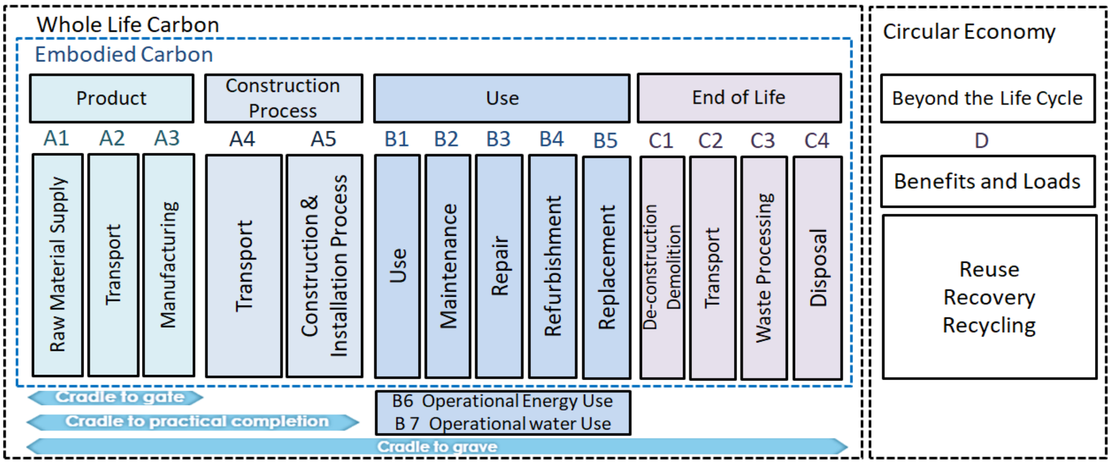

Fig.4. Whole life carbon emission system boundary: En15978(2011)[3)]

4. LCA OF NEXT GENERATION AASHTO-PCI BT-72 GIRDER BRIDGE

LCA evaluating the environmental impacts involves four stages of the life cycle as stated in BS EN15978[3)]: (1) material production stage (A1-A3); (2) construction process stage (A4-A5); (3) user stage (B1-B7); and (4) end-of-life stage (C1-C4)[3)] as shown in **Fig.4**. In the present study, carbon dioxide equivalent in tons (tCO_2e) encompassing all greenhouse gases responsible for the global warming potential is estimated both for BT-72 girder conventional and next generation non-metallic bridge superstructure as a simplified LCA[2)]. It is evident from the previous studies that material production constitutes the maximum share[12),13),14)]. Hence, estimation of tCO_2e in the current study focuses on the material production stage (A1-A3) as shown in **Table 1** indicating that tCO_2e can be reduced by 50% in case of next generation bridge in material production stage. In case of conventional bridge, the maximum share of tCO_2e accounts for NCC as a material component. In reverse, GFRP as a material component contributes to the maximum shares of tCO_2e for the next generation bridge (**Fig.5**).

A comprehensive life cycle cost assessment conducted by Indiana Department of Transportation in 2019 on different bridge superstructures revealed that total life cycle cost of bridges is 2.5 times on an average, mainly contributed by repair, refurbishment and replacement[15)]. As Collings[16)] confirmed that there was a linear correlation between increased cost and higher carbon content of bridges, it is predicted that the whole life carbon emission of a conventional PC girder bridge may increase up to 2.5 times of that of module A, manifesting significant contribution

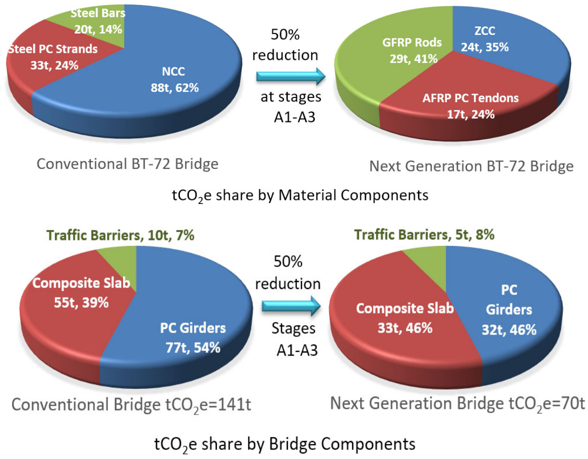

Fig. 5. Carbon emission share of material components and bridge elements[2)]

from module B and C (B+C=1.5×A) as estimated in **Table 2**. Also, based on the LCA by Li *et al*[14)] current estimation anticipates that A1-A3 share 80% and A4-A5 share 20% of embodied carbon of module A as indicated in **Table 2**. According to the studies of Kaewunruen *et.al*[13)], it is anticipated that for the next generation BT-72 girder bridge, Module A shares 88% carbon emission while Module B and C altogether share 12% emission without considering any repair and replacement. Finally, the whole life CO_2e is estimated as 442 tons and 100 tons for the conventional and the next generation BT-72 girder bridge respectively. The predicted whole life CO_2e emission rate of the conventional and the next generation bridges are $1.8t/m^3$ and $0.4t/m^3$ correspondingly. And the highly durable next generation BT-72 girder bridge expected to reduce 77% of carbon emission compared to that of the conventional bridge during its whole lifecycle[2)].

5. LCA OF THE NEXT GENERATION NON-METALLIC BUTTERFLY WEB BRIDGE

Comparative studies on carbon emission of the non-metallic butterfly web bridge were performed based on the 2nd Generation Non-metallic Bessodani Bridge[4]. A similar precast segment box girder bridge with external post-tensioned steel cables constructed with normal strength concrete considering 1.1 times weight of the Bessodani Bridge is taken into account for the comparison. Moreover, the next generation non-metallic butterfly web bridge is studied where the ultra-high strength fiber reinforced concrete is replaced by STC-ZERO. In case of the conventional box girder bridge, carbon emission in Module B and Module C altogether due to maintenance, repair, replacement, dismantling and disposal is considered 1.5 times of the emission in Module A. In case of the highly durable 2G Non-metallic Bessodani Bridge and the Next Generation Non-metallic Bridge with STC- ZERO, carbon emission due to maintenance, repair and replacement in Module B is not taken into account. It has been revealed from **Fig. 6** that carbon emission of the newly constructed 2G Non-metallic Bridge in module A is almost equal to that of the conventional box girder bridge owing to the use of ultra-high-performance concrete. However, the whole life carbon emission of the highly durable 2G non-metallic bridge is predicted to be reduced up to 52% as repair and replacement is not needed[2] (**Fig.6**). Further, the whole life carbon emission is predicted to be decreased by 69% as compared to the conventional bridge since there is no share from Module B due to the non-existence of bridge deterioration[2].

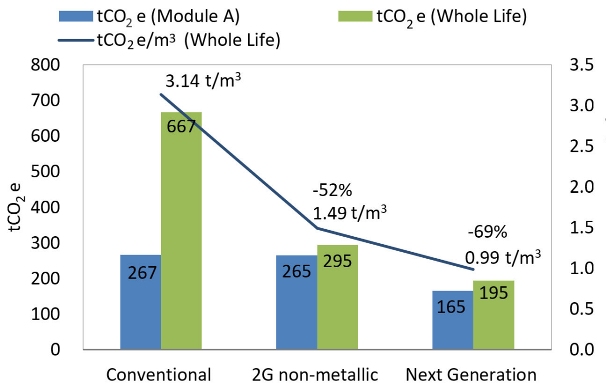

Fig. 6. Carbon emission of conventional PC box girder bridge, 2G non-metallic bridge and next generation non-metallic bridge with STC-ZERO[2]

6. CONCLUSION

Current paper presented a challenging design concept of a next generation ASSTHO-PCI bulb tee (BT-72) prestressed girder bridge with a fusion of STC-ZERO and non-metallic FRP reinforcements. The whole life cycle assessment has revealed that the next generation non-metallic BT-72 girder bridge reduces the equivalent carbon emission at around 77% compared to that of conventional bridge of same size. Further, the whole life carbon emission of the next generation non-metallic butterfly web bridge is anticipated to be reduced up to 69% as compared to the conventional bridge. Since, there is no repair and rehabilitation requirements, the ultra-high durability low carbon next generation bridges with extended lifetime are expected to significantly reduce the whole lifecycle cost compensating the initial increased cost for low carbon highly durable advanced technologies.

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