Recent developments of ballastless tracks in high-speed and urban lines

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Abstract—This paper introduces the recent advances in ballastless tracks in recent years and discusses different systems in use and their applications. The idea is to provide more reliable foundation for track by replacing ballast with materials such as concrete and asphalt. Concrete is the most widely used material in ballastless tracks and different slab track configurations have been in service. However, asphalt can also be a good alternative for ballast especially where noise and vibration reduction is required. This paper discusses advantages and drawbacks that may be encountered in their construction. Other types of ballastless tracks including embedded rail systems will be discussed and recent advances and design process will be introduced.

Keywords—concrete slab, Ballast, Asphalt, embedded rail

I. INTRODUCTION

Numerous studies have been conducted during recent decades to investigate the performance of different infrastructure systems and how to improve them [1], [2], [3]. Railway track as traditionally lies on ballast or coarse-graded granular materials. The role of ballast in track is to distribute stresses from wheels of vehicles to the substructure, drainage of the system and to provide a foundation for sleepers. Based on many experiments and analyses that have been done in recent decades, ballasted track is susceptible to many defects [1], [4], [5]. Therefore some solution have been proposed to reduce the problems caused by ballast in railway track such as using geogrids [6] and adding Bituminous Subballast Layers [7], [8]. Due to degradation of ballast material as the accumulative loading of vehicles increases, the analysis of ballasted track is challenging for railway engineers and simple linear models of track are proved to be unsophisticated [9]. It is also shown that ballast tends to amplify the geometry deficiencies in track [10], [11], [12]. This problem especially arises for high-speed tracks and metro lines. As a result, there have been some attempts to replace the troublesome ballast with more reliable materials with little maintenance.

The emerge of ballastless track started with introducing slab as a substructure for railway track [1]. Different ballastless tracks have been introduced during the recent decades. Most of the new track design concentrated on replacing ballast with concrete slab, however, some other materials have been utilized and the results show that they have been successful in providing a reliable foundation to withstand loads from traffic. Ballastless tracks are especially popular in bridges, tunnels and light rail system where ballast replacement and maintenance is either very difficult or time consuming [13], [14]. Despite all advantages of ballastless tracks some environmental issues such as noise and vibration and high construction costs stop ballastless track from developing fast [15]. In this case, it is required to consider some elastic layers to reduce noise and vibration which resulted in producing floating slab tracks [16], [17].

Embedded rail system and green track in urban railway is another example of solutions to the issues in ballastless tracks. They provide an environmentally friendly superstructure for track while having the required standards introduced by railway codes [18]. There are also other track configuration such as ladder track which have been used in special cases such as desert area or bridges where maintenance of conventional ballasted track or other types of slab tracks are difficult [19].

This paper discusses different configuration of ballastless track and their advantages and drawbacks and discuss their application in railway track. It is also the purpose of this paper to provide recommendation on the use of ballastless track in different conditions. Among many forms of ballastless track, three kind of them is evaluated here namely; slab track, asphalted track and embedded rail systems.

II. SLAB TRACK

High-speed rail which was first introduced in Japan now have been prevalent in different part of the world. In Europe some high-speed line between countries have been constructed and in the United States, California high-speed rail is under construction. It is shown that high-speed rail produces grate dynamic forces and causes track defects in case of ballasted track, as a result, a lot of maintenance activity is required to maintain track in standard condition [20]. Slab track offers a solution to this problem by providing a more reliable track support. There are different slab track configurations that have been used in recent years such as Japanese slab track Shinkansen and German slab track Rheda 2000 [21].

Shinkansen high-speed rail track started in Japan in 1950s and has been developed to five lines with the length over 2200 km. As figure 1 shows the whole slab track system act as a monolithic component. It includes sleepers which is embedded in concrete slab [22].

In Germany, a number of ballastless tracks have been in operation. Rheda 2000 is the most widely used slab track and have successfully constructed in different regions [23], [24]. This system has undergone many changes since 1970s. The originally mono-block sleeper system turned into bi-block sleepers and a truss shaped reinforcing connects the two parts of the sleepers. Rheda system can be used as a mass-sparing system to reduce vibration from railway track, as a result, this type of track is one the most popular ballastless tracks currently in service.
The application of slab track in North America is increasing. The early use of slab track in transit system in the US is for tunnels and bridges. In most cases, slab tracks have been modified to reduce noise and vibration. Such designs can be found in Washington D.C metro system and Long Island Railroad [23].

Decades operation of slab track proves the effectiveness of this system in different types of tracks. However, studies show that some kind of defects can be developed in slab track systems. For example, Poveda et al [26] evaluated fatigue life and time-dependent behavior of slab track by using a three-dimensional finite element model. Based on their findings, for a 100 year fatigue life guarantee, the compressive strength of concrete should not be less than 50 MPa. It is also shown that 17 cm slab track is adequate for a low level fatigue damage structure. They also conducted a research on the effect of fastening system on the fatigue life of the system and concluded that with increasing the stiffness of the fastening system, the risk of fatigue damage increases.

One of the most applications of slab track is the tracks in tunnels where maintenance is difficult to perform. In this case, damage due to inability to drain water from track may be significant. To response to this problem, Cao et al [27] have done a hydro-mechanical analysis to consider the coupling effect of train load and water on the damage mechanism of slab track. Their results indicate that the train speed is an important factor in propagation of cracks in slab tracks. According to the authors, slab track can be considered safe if the length of crack is less than 0.4 m.

Track settlement is the most important concern regarding slab track performance. The measurement and analytical analyses show that it depends on the stiffness of the subgrade and with increasing the subgrade’s stiffness, slab track settlement reduces. The elasticity of slab track is primarily maintained by fastening system and rail pads [28].

As mentioned, application of slab in railway track increases the level of vibration and may cause disturbance for people living near track. One solution to this problem is the use of floating slab tracks or using elastic layers under slabs. There are two aims of using under sleeper or under slab pads: first, to add elasticity to the track and second to change the natural frequency of the system to avoid resonance. This issue has been investigated by many researchers. For instance, Kuo et al developed a mass-spring-damper model to perform a sensitivity analysis on the effective parameters on the vibration of floating slab tracks. They considered a number of parameters including the mass of slab, slab bearing stiffness and train speed. Based the results obtained, reducing the stiffness of the system would result in lower vibration level but increase the deflections. They proposed a combination of soft slab pads and stiff fastening system. It was also concluded that arbitrary design of slab tracks may amplify the vibration and increase the track settlement beyond the acceptable range [29].

The need to develop appropriate criteria for design of slab tracks led to some design specifications developed by railway codes. For example, America Railway Engineering Maintenance of way Association (AREMA) suggested some criteria for slab track design. It is recommended that rail deflection should be limited to 6 mm and stress on compacted subgrade should not be more than 138 KPa. Cracks in concrete should be held tight by longitudinal reinforcement. The distance between cracks should be 0.8 to 2 m. Hence, longitudinal reinforcement of 0.7 to 0.8 percent of cross sectional area of the concrete slab is usually required [30]. Other criteria proposed by international Union of Railways and Euro codes, but majority of the design suggestion relies on the ballasted track design specifications [1].

Fastening system is another important part of slab track design that should be considered in design process. Fastening system is especially important in case of slab track because it provide the required elasticity of the system and reduces vibrations from train loads and furthermore, adjustable fastening system can compensate for errors in construction and geometry deficiencies which is always a concern in slab track design. Previous studies have shown that flexible fastening system are capable of providing a reliable support for track and have enough life cycle cost for a slab track system [31]. For direct fixation fastening the following criteria have been proposed [32]:

- The stiffness constant should be between 15.8 and 52.5 KN/mm
- Railhead lateral deflection should be limited to 7.6 mm
- Longitudinal resistance of fasteners should be more than 10.7 KN
- The maximum ratio of dynamic to static stiffness should be 1.5
- No failure should occur during 3 million cycles of vertical and lateral loading.
No failure should occur during 1.5 million cycles of upward and downward vertical loads.

III. ASPHALT IN RAILWAY TRACK

Ballasted track is prone to track defects and needs periodic maintenance to keep it in good condition which increases the operation costs. The idea of replacing ballast with more rigid subgrade is not limited to concrete. Asphalt which is widely used in pavements is another alternative. It is shown that asphalt will increase the overall stiffness of track structure and as a result increase the bearing capacity of the track. This is especially important for freight track. Asphalt is also resistant to vertical deformations. The use of asphalt in track prevents the mixture of fine aggregates of subgrade and coarse material of ballast. Hence, longer track life will be achieved [33]. Some studies on the application Rubber Modified Asphalt Concrete (RMAC) demonstrated its effectiveness in reducing noise and vibration from railway track [34]. To investigate this issue, some numerical and experimental works have been performed. For example, Wang and Zeng employed finite element code ABAQUS to compare the use of different materials including RMAC, asphalt concrete, concrete and ballast as trackbed and their effect on the vibration level. Based on the outputs of the software, RMAC has the best effect in vibration attenuation and lower track vibration by 35.7% compared to ballasted track. For concrete trackbed vibration amplification was observed in some cases [35].

There are two kinds of asphalt application in railway track have been reported in the literature. The first application is the called overlay which means ballast is totally replaced by asphalt and it directly lies on subgrade. The second experience with asphalt in track is called underlayment which means there is a layer of asphalt under ballast to provide a more stable foundation for track. (Error! Reference source not found.) The University of Kentucky developed a computer program that can be used specifically for analysis and design of asphalt in railway track. Two failure criteria of Hot Mix Asphalt (HMA) trackbeds incorporated in the code: maximum horizontal tensile strain at the bottom of asphalt layer for fatigue cracking and maximum compressive stress on the surface of subgrade for permanent deformations [36]. The results of using HMA in track indicate that HMA does not show typical failure modes in highway pavements. There are two reasons for that; first, the asphalt is not in direct contact with vehicle and dynamic train loading distributes and damps by sleepers and fastening system. Second, the asphalt in track is not exposed the hot and cold weather. Hence, rutting and cracking due to hot and cold weather cannot affect the life cycle cost of track [37].

![Fig. 2. Rheda 2000 slab track [30]](image1)

![Fig. 3. Application of asphalt in railway track [34]](image2)
IV. EMBEDDED RAIL SYSTEMS

Embedded rail system can be categorized as slab tracks because it needs a rigid foundation for rail to support it. The major difference between embedded rail tracks with other types of track structure is the rail installs inside the concrete. Consequently, no sleeper is required. This configuration is especially effective for urban areas where special route for rail vehicle is not provided. Another advantage of using embedded rail system is that rail is supported by the concrete and as result, the stress distributes all over rail length. Since rail and substructure are not accessible, one issue that needs to be addressed in this type of track is the drainage. Failure to provide an effective drainage system will result in track failure. To solve this problem, rail is embedded with some types of elastomers and PVC tubes placed on both sides of the rail [18]. Error! Reference source not found. depicts the embedded rail track and its components.

Another possible configuration is embedded rail in asphalt. Huurman et al [38] analyzed embedded rail in asphalt by assuming cement-filled porous asphalt as filler. Since the rail is embedded, rail height was reduced to 80 cm. The substructure used in the analyses consists of 200 mm stone asphalt concrete on 200 mm unbound granular material. A finite element model using ANSYS and CAPA-3D developed to consider the performance of embedded rail in asphalt. The results show that fatigue or permanent deformation recorded by the author is in the acceptable range and also the maximum stresses in the asphalt is much lower that the allowable stress.

Transit Cooperative and Research Program (TCRP) in the track design manual divided embedded rails into three groups: (1) non-resilient embedded tracks; where rail is located on a hard base slab and embedded in a concrete with no elastomeric materials around. Obviously, high track stiffness will not allow heavy trains to run on non-resilient tracks. TCRP suggested that concrete or asphalt without elastomeric components should not be used in track. (2) Resilient embedded track; in this case, rail is supported by a resilient base with a moderate modulus of elasticity. The track can absorb some noise and vibration from traffic and vehicle load distribute evenly along the rail. (3) Supper resilient embedded track; this kind of track may be used where hospitals, libraries, vibration sensitive equipment and other facilities that have strict criteria on vibration control are located near track. Supper resilient track consists of two concrete slabs. The initial base slab is constructed on the subgrade and the second slab includes the track components. Resilient isolators are positioned between the two slabs. This type is structure can attenuate the most noise and vibration from railway track [39].

V. OTHER BALLASTEDLESS TRACKS

As it might be applicable for ballasted track, ballastless track may need special treatments for special situations which usually happens when track is located on soft soils without enough bearing capacity to resist loading from trains. Soft soil causes two kind of problems: (1) trackbed settlement (2) vibration amplification. The vibration problem usually happens in case of high-speed trains where the train speed is more than Rayleigh wave velocity in soil. Many researchers show that at speeds near Rayleigh wave velocity great vibration occurs in track and neighboring structures. Hence, substructure needs to be modified [40], [41].

Pile-slab is a form of ballastless track for high-speed lines. It consists of a reinforced concrete foundation and a series of piles joined to the structure. Error! Reference source not found. shows the pile-slab track. Currently there are not any design standard for this track and other codes have been used for analysis and design. However, this approach will not always lead to satisfactory results. For example, assuming structure a plate girder bridge produces different results because the connection mode between slab and pile is different from that between beam and pier [42].

In urban areas, other special track configuration have been developed. Grass track is an environmentally friendly track structure used in Europe. Track consists of adjustable steel sleepers which are embedded in concrete piles. Plastic pads are used for fastening of rails and the space between the piles are filled with sand and a layer of soil on the top. The grass seeds then are placed into the soil. The experience of using this track showed that, compared to other slab track systems, it requires more maintenance [43].

CONCLUSIONS

This paper presented different alternative to the conventional ballasted track to provide more reliable track.
structure. There have been a number of track design developed in recent years. Among those, slab track is the most widely used track system. Asphalt cab also be placed in track substructure to provide support for rail and sleeper and finally in urban area, embedded rail systems is popular. A review on the literature showed that although it is proved that ballastless track is almost “maintenance free” in most cases, however grater construction costs compared to ballasted track make it uneconomical in many situations. As a result, in many countries, ballastless tracks are limited to tunnels, bridges and special track works. Another issue regarding ballastless track is the lack of established design methods and standards. In some cases, there are guidelines presented by railway agencies, but detailed design methods have not been introduced yet and design specifications of ballasted track are used in most cases. The previous experience of ballastless track indicates that a comprehensive cost analysis for the life cycle of the project needs to be performed before deciding to remove ballast from track.

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REFERENCES


