“Transrapid Guideway: Safety Assessment on A New Design of Long Stator Pack Fastening”

Winfried Steinert & André Bohlscheid
TÜV Rheinland InterTraffic GmbH, Cologne, Germany

ABSTRACT: TÜV Rheinland InterTraffic GmbH as a member of TÜV ARGE VME is one of the notified expert organisations for the TVE (Transrapid Test Facility Emsland, Germany) responsible for safety assessment. In the course of the activities carried out, TÜV Rheinland InterTraffic GmbH assessed the long stator pack fastening of new guideway beam prototypes which are under trial on the TVE. To reduce the number of fastening elements of the stator packs at these guideway beam prototypes, the stator packs are attached by inserts and are tensed against the machined concrete or the cladding tube directly. While the old fastening contained separate redundancy elements (cold redundancy, redundancy clutches) that were only used upon failure of the first fastening level, the new approach is based on over-dimensioning of fastening elements (warm redundancy). Due to the abdication of conventional redundancy of the stator pack fastening, demands on load bearing capability and failure detection must be particularly taken into account. In order to follow a clear assessment approach and to provide safety evidence, test and acceptance criteria have been derived which cover test, operational and maintenance aspects. The experiences gained and the first results of the assessment on the design of the stator pack fastening without redundancy elements are reported.

1 INTRODUCTION

1.1 Role of TÜV Rheinland InterTraffic on TVE

The Transrapid test facility (Transrapid Versuchsanlage Emsland, TVE) was built from 1979 to 1987.

From the beginning the TVE was subject to the law for test facilities (Versuchsanlagengesetz). According to this law the relevant approving authority for the TVE is the Technical Supervisory Body (Technische Aufsichtsbehörde TAB) of Lower Saxony (Niedersachsen) within the State Road Construction and Traffic Office of Lower Saxony (Niedersächsisches Landesamt für Straßenbau und Verkehr, NLStBV).

In the course of the approval of the operation regulations according to §12 (4) of the law for test facilities the approving authority notified experts/ expert organisations to monitor the observance of the operation regulations. One of the two notified expert organizations is the TÜV Arbeitsgemeinschaft Versuchsanlage Emsland (TÜV Arge VME), a joint venture of TÜV Rheinland InterTraffic GmbH (TRIT) and TÜV Nord. TRIT within the TÜV Rheinland Group as a member of the TÜV Arge VME is examining the following subsystems: Maglev vehicle, operation facilities including service vehicles, operation control system, switches and transfer table, guideway equipment (stator packs and –fastening, guidance rail, gliding rail, power rail), propulsion, Inductive Power Supply (IPS). Furthermore TRIT is responsible for EMC, system technology, interfaces and the set of operation regulations. The second member of TÜV Arge VME, TÜV Nord, is responsible for the electrical equipment of the facilities, of the guideway equipment and of the propulsion, furthermore for ESD and lightning protection.

The second expert notified by the approving authority is Dr.-Ing. S. Droese from the Institut für Baustoffe, Massivbau und Brandschutz (iBMB) at the TU Braunschweig, who examines the main structure of the guideway.

2 NEW SOLUTIONS FOR STATOR PACK FASTENINGS WITHOUT REDUNDANCY CLUTCHES

2.1 Principles of the stator pack fastenings

During the previous and this year guideway beam prototypes of three manufacturers have been installed for testing at the TVE. At these it has been passed on the redundancy elements (redundancy clutches) of the stator pack fastenings used until now.

In the following only the two versions of the stator pack fastenings without redundancy clutches provided for the concrete guideway beam prototypes are described. For both described versions bolts of a thread diameter of M 20 and property class of 8.8 are applied.

One version is provided with two longitudinal concrete rails on both girder sides. These concrete rails are adapted to the exact dimension by beveling. The stator packs are tensed against these machined concrete rails by attachment bolts screwed into screw nuts witch are set in concrete. The horizontal forces are transmitted into the guideway beam by friction between stator pack and concrete surface.

The boreholes in the concrete provided for the attachment bolts are protected by a cladding tube.

Due to this design the number of devices being necessary for stator packs fastening is reduced to washers, nut sets, cladding tubes and attachment bolts.

For the other version of guideway beam prototype considered here the anchors of the guidance rail and of the stator packs fastening are composed to an unit.

The attachment of the guidance rail fastenings and of the stator pack fastenings is provided by welded mounting parts set in concrete. The guidance rail is anchored at the concrete by being welded to the upper and to the lower lugs.

The stator pack fastening is provided by prestressed bolts screwed into nut sets which are set in concrete at the upper lugs. For this purpose there are two tube jointing sleeves at each lug. These tube jointing sleeves are put through the lower and upper lugs.

The bolt forces are transmitted into the concrete mainly by the anchor of the upper lugs.

The tube joint sleeves are protruding at the cantilever's underside. Due to this the stator packs are tensed against the tube joint sleeves.

3 STATOR PACKS FASTENING AT PRESENT

In a first approach the primary stator pack fastening consisted of four bolts (M 12; property class 10.9) without redundancy. By-and-by the thread diameter has been increased to M 16 at first and than followed by M 20 (property class 8.8).

Furthermore the number of attachment bolts has been increased to six.

In addition a cold redundancy has been provided at all stator pack fastenings, becoming operative if parts of the primary stator pack fastening fail. The type approved stator pack fastening provided with redundancy clutches for the attachment bolts of the outer cross–beam slot is depicted in figure 1 and 2.

The primary attachment is provided by a prestressed screw connexion. If the primary attachment bolt fails the stator pack is held on the cantilever's slots. The clearance between the cantilever and the slot tie-bar is dimensioned in a way that a failed primary stator pack fastening is detected automatically (failure detection).

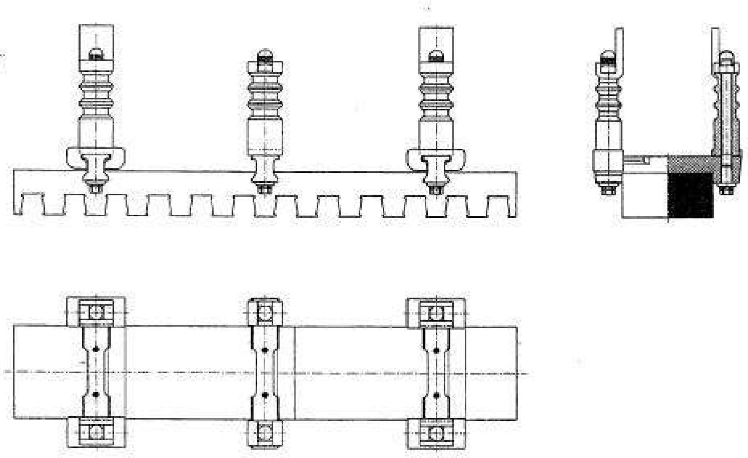

Figure 1: stator pack fastening, type approved (/1/)

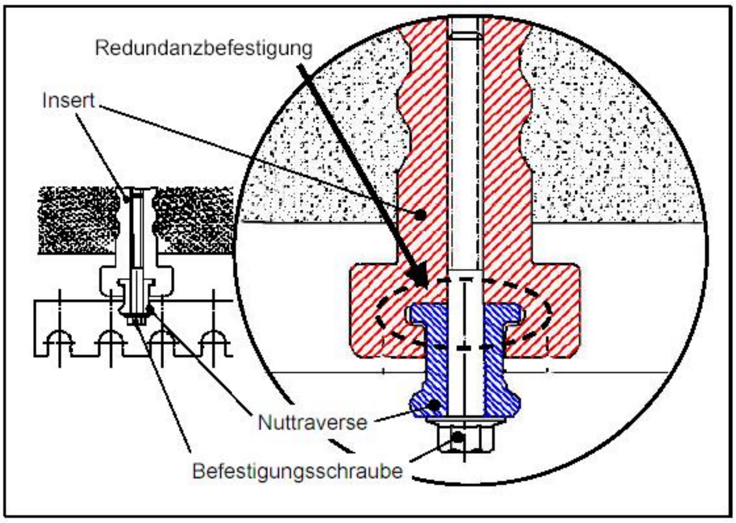

Figure 2: stator pack fastening, mounted (/2/)

4 REQUIREMENTS FOR STATOR PACK FASTENING

4.1 General

The stator packs and the windings are composing the linear synchronous stator propulsion system.

The stator packs provide the transmission of the forces resulting from bearing, guiding and propulsion and service braking respectively. The forces are transmitted via the stator pack fastening into the guideway beam.

Since the stator packs with their fastenings are a part of the electrical machine linear motor the requirements for machine construction in addition to the Transrapid-specific requirements have to be taken into account. This especially concerns the demands on tolerances and the dimensioning of the bolts. The tolerances and dimensioning of bolts used at civil engineering are not sufficient in the case under consideration.

The following relevant demands on the stator pack fastening are derived from the basic requirement of preventing collision between stator pack and levitation magnet[1]

- The stator pack must be kept in the specified position reliably during the entire service life.
- In case of failure of fastening elements a safe service operation must be ensured for a period to be proved.
- Failure detection and maintainability must be ensured.
- The critical lowering of the stator pack (> 4 mm vertical offset between two adjacent stator packs) must be prevented.

These requirements are based on the following concepts[2]:

Safe-Life:
Availability during the entire service life. Realization can be met by:

> Failure exclusion based on fatigue strength dimensioning and sufficient tests at production and at maintenance phase

or

> redundancy within fault tolerance

Fail-safe: At failure occurrence the safe state is kept.

With DIN 25201 T2 “Konstruktionsrichtlinie für Schienenfahrzeuge – Schraubverbindungen” (guideline for design of rail vehicles – screwed joints) an additional normative demand regarding the design of fastenings with redundancy is available. According to DIN 25201 for risk class H (high) a redundancy for operational breakdowns is required.

For the design two options are selectable:

- Higher number of bolts than required by calculation
- additional device activated if the primary attachment fails.

If the evidence that the load capacity of the remaining attachment bolts regarding load capacity and fatigue is sufficient after one or more attachment bolts failed can be proved, the remaining attachment bolts can be regarded as redundancy.

In this case has to be verified, that the remaining attachment bolts are fatigue endurable under these increased loads or that the fatigue strength of these attachment bolts is covering the period specified for detection of the failure.

4.2 Ability to approval and demands on qualification

The matter of ability to approval of a concept without cold redundancy is especially dependent on answering the following questions:

- How can the failure of the stator pack fastening be detected safely in time?
  - At this “failure” means: Due to critical lowering of a stator pack the safety of operation does not exist any longer.
  - At this “in time” means: The error status must be removed from a critical lowering definitely.
- What’s the extent of stator pack lowering (offset) resulting from different failure scenarios of stator packs fastening (failure of 1 to up to 3 attachment bolts)? What’s the extent of the residual load capacity and the residual durability?
- Is there a risk of loss of pre-tensioning force caused by self loosening?
- Does a bending load for the attachment bolts exist?

4.3 Failure detection und error propagation

With respect to the operating conditions and the possibilities of inspection at TVE and with respect to the limited number of guideway beam prototypes and also limited number of stator pack fastenings, the application of the new stator pack fastenings without redundancy can be regarded as uncritical for TVE.

For a specific application further investigations regarding failure detection are necessary.

At present stator pack offsets from 1.5 mm can be detected online and those from 0.7 – 0.5 mm can be detected offline by the on-board measurement system at TVE.

Because stator pack offsets of 0.3 mm are expected at maximum if two attachments bolts fail, this failure can’t be detected securely by the current device.

Regarding an automatic detection of failed stator packs fastenings the following could be regarded as basis for a solution:

- Inspection ride with increased levitation forces.

---

[1] According to /2/

[2] According to /3/

- Determination of response spectrum of stator packs
- Optical techniques

If optical techniques are applied, it has to be investigated, how broken attachment bolts can be detected, if the bolt head is still in its original position.

4.4 Elimination of systematic failures

The following systematic failures can cause a failure of the attachment bolts:

- Loss of pre-tensioning results in fatigue breaking caused by axial repetitive stress. The loss of pre-tensioning can have the following reasons:
  - Systematic (and random) assembling failures.
  - Loosening due to subsidence.
  - Partial loosening caused by relative movements and slip respectively.
- Tangential deviation of attachment bolts, inclined bolt head / nut set or loads transversal to the screw axis can result in fatigue bending breakage.
- Insufficient material ductility can result in brittle fracture.

4.4.1 Tolerances

The tolerances being usual at the civil engineering and machine construction are interacting at the considered stator packs fastenings.

Due to tangential deviation of the attachment bolt or inclined bolt head / nut set or bolts secured against loosening, but loaded transversal to the screw axis, fatigue bending breakage can occur, the permissible tangential deviation of the attachment bolt is to be limited extensive or the impact of bending load must be investigated.

4.4.2 Materials

In the past at TVE hydrogen-embrittlement-induced cracking at attachment bolts has been detected.

This has to be avoided by adequate material-selection.

For the selected material combination it has to be demonstrated, that material-dependent corrosion is eliminated.

4.4.3 Slippage

Because the required clamping force is dependent on the friction coefficient between cross-beam slot and cantilever, the friction coefficient must be determined by test.

It is to be investigated, to which extent possibly occurring slippage has an impact on the surface properties of the contact area.

4.4.4 Subsidence, surface pressure

The compliance with the permissible surface pressures at the cross-beam slot and at the contact area of the guideway beam has to be proved for the maximum pre-tensioning force. The specific subsidence of concrete has to be taken into account.

4.4.5 Loss of pre-tensioning force

Regarding the stator pack fastenings considered here, the following possibilities of loss of pre-tensioning force are relevant:

- Loosening due to subsidence. At this the residual clamping force emerging after release of the connected components due to working load and after (loss of pre-tensioning force caused by) subsidence is decisive.
- Partial loosening caused by reversal of the self-locking between contact areas involving fatigue breakage. Under dynamic transversal load loosening can also occur if transversal movements (slip) between the tensed components emerge.

4.4.6 Assembly

By means of assembly instruction it is to be demonstrated, how:

- The perpendicular assembly of the attachment bolts and the compliance with the tolerances regarding the the tangential deviation are assured.
- The pre-tensioning force of the attachment is assured and checked.

4.5 Approach for qualification of the new solution: Verification

The approach for qualification of the new solution for concrete guideway beam prototypes can be classified into the three topics described in the following:

- Theoretical determination of loads and calculation
- field tests at TVE
- rig testing

4.5.1 Load assumptions

At present the load assumptions are based on the „Magnetschnellbahn Ausführungsgrundlagen Fahrweg Teil II Bemessung“ (/4/)

In addition to the local dynamic factors the increase factors caused by the dynamical magnet forces must be taken into account.

Due to the varying magnet forces resulting from gap control especially at low speed or levitation at standstill natural frequencies of guideway elements can be affected. Therefore these loads resulting from these frequencies must be proved.

4.5.2 Theoretical investigations / determination

For qualification of the stator packs fastenings without redundancy the following calculations have to be conducted:

- Evidence of load capacity (paying regard to different failure scenarios of stator pack fastening). With estimated dynamic factors to some extent.
- Determination of the lowering of the stator packs and of the displacements in z-direction respectively (paying regard to different failure scenarios of stator packs fastening).
- Screw calculation according to VDI 2230 (/5/) for the attachment bolt under maximum load having regard to different failure scenarios of stator pack fastenings and determination of residual durability.
- Investigations regarding the longitudinal forces and occurrence of slippage.
- Determination of the natural frequencies and eigenforms (paying regard to different failure scenarios of stator packs fastening).

Additionally the technical documentation must include:

- Measures provided to avoid systematic failures.
- Investigation of tolerances regarding the tangential deviation of the attachment bolts; where applicable calculation of the bending load. QA-documents documenting the existing tangential deviation.
- Assembly instructions.
- Initial start-up specification for TVE and for specific application.
- Measures provided for decreasing random failures.
- Investigations and determinations regarding failure occurrence, fault tolerance and inspection possibilities and intervals (inspection manual for TVE and for specific application).
- System technical release of the fastening concept, of the windings and of the winding retainer.

4.5.3 Field tests at TVE

For qualification of the stator pack fastenings without redundancy the following test at TVE are to be provided:

- Determination of the dynamic behaviour of the stator packs (paying regard to different failure scenarios of stator packs fastening, different vehicle speeds and at guideway beam's centre and outer areas), dynamic factors, resonance behaviour.
- Determination of the bolt forces and deformations (paying regard to different failure scenarios).
- Determination of the loss of pre-tensioning force of the attachment bolts.
- Tests regarding the automatic detection of failed stator packs fastenings.

4.5.4 Rig testing

For qualification of the stator pack fastenings without redundancy the following tests are to be conducted:

- Determination of the fastening torque and of the pre-tensioning force of the attachment bolts.
- Determination of the friction coefficient between the stator pack and cross-beam slot respectively / concrete and tube jointing sleeve.
- Dynamic fatigue tests (paying regard to different failure scenarios of stator packs fastening).
- Investigations of the dynamic behaviour of the mounted stator packs without winding (paying regard to different failure scenarios of stator pack fastening).
- Determination of the relative movements at the stator packs fastening.

5 SUMMARY AND FORECAST

From the author's point of view the considered stator pack fastenings represent a cost-reducing and innovative development of the present fastening concept.

However especially with respect to the demands on failure detection at a specific application an improvement concerning the possibility of inspection is regarded as necessary.

To generate a comparable level of qualification for the several versions of stator pack fastenings without redundancy in spring 2006 experts accredited by Eisenbahn-Bundesamt (EBA) have discussed and worked out "Hinweise zur Nachweisführung" (recommendations for verification).

The release of this guideline is scheduled for 2006.

The development of additional concepts for stator pack fastenings without redundancy clutches is preferable.

We hope, that the current discussion concerning the demands on a qualification approach will make a contribution to this.

This article is based on the author's state of knowledge of may, 1st 2006.

6 REFERENCES

/1/ Technischer Bericht MSB Systemdokument Statorpaketbefestigung Betonfahrweg, Ausga-

be 21.08.1995
Thyssen Henschel Magnetfahrtechnik

/2/ Magnetschnellbahn
Ausführungsgrundlage Fahrweg, Teil I, Übergeordnete Anforderungen
MSB Fachausschuss Fahrweg
Entwurf 06.04.2006

/3/ Magnetschnellbahn
Ausführungsgrundlage Gesamtsystem
MSB Fachausschuss Gesamtsystem
Entwurf 06.04.2006

/4/ Magnetschnellbahn
Ausführungsgrundlage Fahrweg, Teil II, Bemessung
MSB Fachausschuss Fahrweg
Entwurf 06.04.2006

/5/ VDI 2230 Blatt 1
Systematische Berechnung hochbeanspruchter Schraubenverbindungen
Verein Deutscher Ingenieure
Berichtigter Nachdruck 2003-10