Bridge Maintenance, Safety, Management, Health Monitoring and Informatics – Koh & Frangopol (eds)
© 2008 Taylor & Francis Group, London, ISBN 978-0-415-46844-2

Consideration of dynamic traffic action effects on existing bridges at ultimate limit state

E. Brühwiler & A. Herwig
École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

ABSTRACT: Dynamic energy due to ultimate limit state relevant traffic scenarios may completely be dissipated by plastic deformations without failure of the bridge element. If the structure shows significant strain hardening behaviour, the maximum static effect is allowed to reach the elastic limit. This paper presents a study of the dynamic action effects on the structural behaviour of "ductile" structural bridge elements showing significant deformations in the post-elastic regime. The results allow deriving dynamic amplifications factors valid for the structural safety verification at Ultimate Limit State (ULS), i.e. the dynamic amplification factor may be set to 1.0 if sufficient dissipation capacity in the structural element is identified.

1 INTRODUCTION AND BASIC APPROACH

The objective of the examination of existing bridges is to show that for actual traffic load action effects the requirements are fulfilled regarding:

- the Ultimate Limit State ULS (involving ultimate resistance and stability of the structure) through the verification of the structural safety,
- the Fatigue Limit State FLS through the verification of the fatigue safety,
- the Serviceability Limit State SLS (involving functionality, comfort of persons, appearance) through the verification of the serviceability.

Updated traffic models are needed for all three kinds of verification. A rational approach to define updated traffic loads considering allowable traffic loads for a given line and dynamic amplification factors is given in [Brühwiler 2007].

The basic approach of updating traffic action effects consists in a separate consideration of (static) loads Q and q (axle and line loads respectively), and forces due to dynamic traffic effects. The updated action effect $E_{updated}$ is obtained according to equation 1.

$$E_{updated} = \varphi_i \cdot E(Q_{k,updated}) \tag{1}$$

The (static) traffic loads are updated considering the allowable traffic loads for a given traffic line. Often the characteristic traffic load is multiplied by some "line class" factor to account for the specific line class valid for the considered bridge. This updated static action $Q_{k,updated}$ is the same irrespective of the limit state to be verified.

Forces occurring in the bridge structure due to dynamic traffic action are often expressed by a dynamic amplification factor φ_i (amplifying the static load effect). This dynamic amplification factor depends on the limit state considered, e.g. ULS, SLS or FLS, and the corresponding characteristic structural behaviour.

Bridge structures made of reinforced concrete and steel are designed to show distinctly inelastic, ductile behaviour when attaining ultimate limit state, in order to allow for internal redistribution of action effects and to have insufficient resistance announced by significant deformations.

The dynamic behaviour of the bridge under traffic loads consists in absorption, storage, dissipation and release of energy that is stored in the structure due to dynamic traffic action. For elastic bridge behaviour, this energy stored in the bridge element consists in vibrations leading to increase of deflections and internal forces. Elastic bridge behaviour is considered for fatigue and service limit state. However, for the ultimate limit state, elastic-plastic structural behaviour must be accounted for, and formulas like those commonly given in design codes are then fundamentally wrong since they refer to elastic structural behaviour only.

This paper presents a study of the dynamic action effects on the structural behaviour of "ductile" structural bridge elements showing significant deformations in the post-elastic regime. The results allow deriving dynamic amplifications factors valid for the structural safety verification at Ultimate Limit State (ULS).

2 DISSIPATION OF DYNAMIC EFFECTS AT ULS – THE "GRAVITY EFECT"

At ultimate limit state (ULS), structural elements in reinforced and prestressed concrete and in steel provide significant plastic deformation due to yielding of the steel. In statically undetermined systems, the plastic deformation capacity of the structural elements is usually not fully consumed by internal redistribution of cross sectional forces. In this case, energy induced by dynamic action effects may also be dissipated by the structural element.

However, the so-called "gravity effect" needs to be considered: Both the traffic loads and permanent loads act in the same direction due to gravity, both leading to (external) work (energy) stored in the structural system (Fig. 1). This means that a considerable part of the total dissipation capacity of the structure is "consumed" by the static load effects. Only one part, i.e. roughly the non-linear domain, is available for dissipation of energy due to dynamic effects.

This is in contrast to the case of seismic loading where most dynamic action acts in the horizontal direction and thus perpendicular to the direction of acceleration of gravity meaning that the whole area under the force – displacement curve is available for energy dissipation due to earthquake loading.

Strain-hardening behaviour in the structural response is advantageous for cases where the static action effect is close to the yielding point of the force-deformation curve for the determinant failure mode.

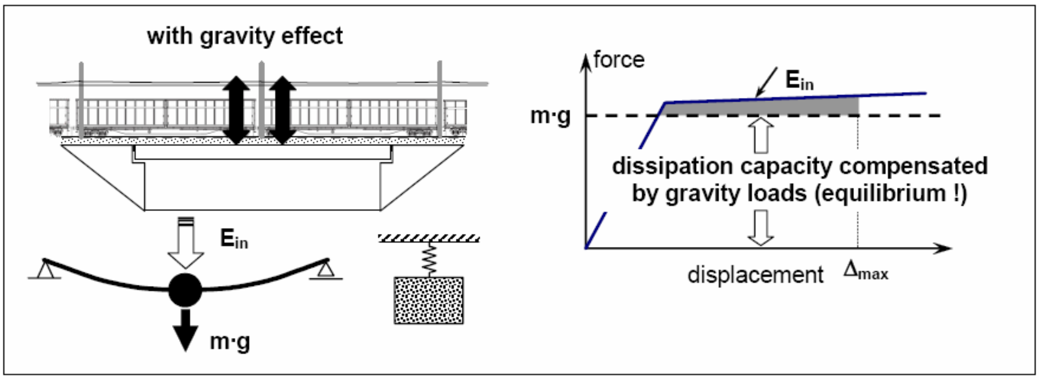

Figure 1: "Gravity effect" and dissipation of energy in the structural response.

(Ludescher 2004) showed by means of simple dynamic models how the external work (energy) due to dynamic action effects (i.e. impact-like events, excitation by road and track irregularities) is dissipated in the structural element before the element fully fails (fractures). In addition, theses studies show that:

- Bridge elements will most probably fail in bending after significant plastic deformation if subjected to excessive dynamic traffic action. More brittle failure mechanisms like

predominant shear failures are unlikely to occur.
- The most unfavourable scenario for bridge elements is the impact-like excitation of passing vehicles by singular irregularities.
- Marked strain hardening in the structural response increases significantly the dissipation potential.
- Resonance oscillation energy may also be dissipated by plastic deformations of the structural element.

The calculations indicate that only a small partition of the remaining dissipation capacity (after taking into account energy dissipation due to the gravity effect and internal redistribution) is needed to dissipate the energy due to dynamic action effects. This will be demonstrated in the following by a numerical example.

3 DISSIPATION OF DYNAMIC EFFECTS AT ULS – SIMPLE CONSIDERATION OF ENERGY BALANCE

The subsequent study shows how the kinetic energy due to dynamic action effects may be dissipated without complete failure of the structural element.

The present example shows a case where the static load effect (including the load factors valid for ULS) reaches the end of the elastic domain. An overloaded truck with a mass m_{ve} = 40t and a very small probability of occurrence passes over a simply supported bridge girder (Figure 2). For a given scenario, there is a dynamic energy introduced into the structural system due to the truck that hits an obstacle leading to impact-like dynamic action. It is assumed that the amount of the dynamic energy corresponds to a dynamic amplification factor of Φ = 1.8 for elastic bridge behaviour (which is a rather high, pessimistic assumption on the dynamic effect).

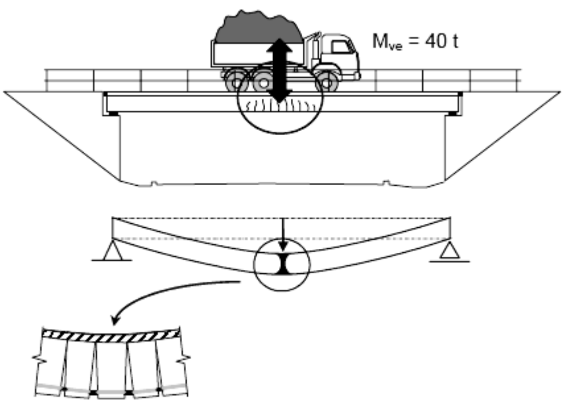

Figure 2: Loading and failure mechanism (plastic hinge at mid-span)

Figure 3 schematically shows the structural response in terms of the moment – rotation diagram valid for the plastic hinge forming at mid span of the bridge girder. After an elastic domain up to M = 3.5 MNm, the bridge girder yields. With increasing deformation, the moment resistance still increases due to the strain hardening behaviour up to 4 MNm.

When the moment due to the total load reaches the yielding point, energy dissipation is only due to plastic deformations with strain hardening. If the ratio M_u/M_y is distinctly above 1.0, the question arises if the reserve may be exploited or not. Whilst the response in general is “no” for the dimensioning of new structures and reinforcing measures, a “yes” may be justified for existing structures where the load carrying is determined more accurately e.g. with non-linear analysis.

The dynamic energy for pure elastic behaviour is calculated with a dynamic amplification factor Φ = 1.8, leading to:

$$E_{el} = (\Phi - 1)^2 \cdot E_{el,stat,ve} \tag{2}$$

The resulting maximum (elastic) moment is clearly above the bending capacity M_u (Figure 3). The structural safety would not be fulfilled according to a conventional verification of structural safety (and the bridge would be strengthened or replaced). The consideration of the energy dissipation capacity due to “ductile” structural behaviour in the post-elastic domain, however, allows proving that the structural safety is sufficiently high. In the following, it is shown how much of the total energy dissipation potential is used for the dissipation of the energy due to dynamic traffic effects.

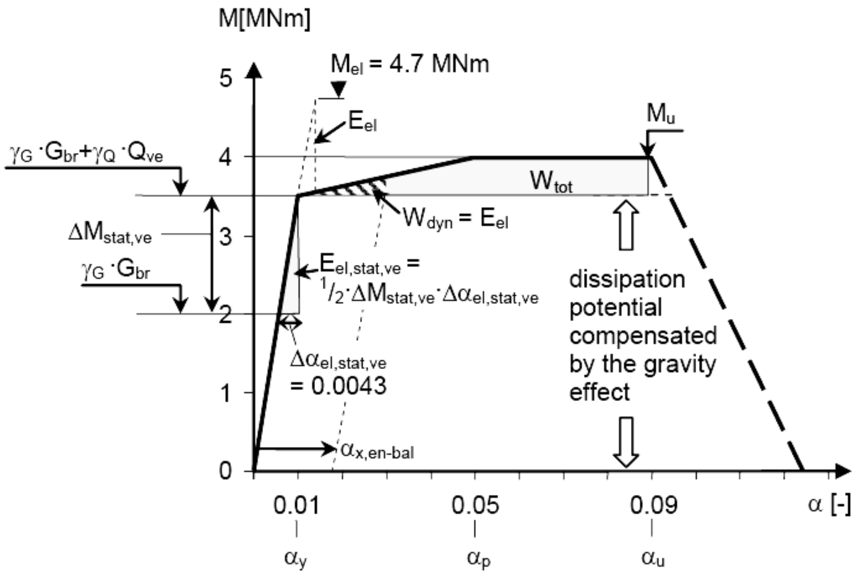

Figure 3: Structural response (work diagram) of the plastic hinge at mid-span of the bridge girder.

In Figure 3, the surface W_{tot} is the energy dissipation potential of the plastic hinge at mid-span of the bridge girder for the given total load level consisting of the permanent load and the vehicle load. This energy dissipation potential is drastically reduced by the “gravity effect”.

The consumed dissipation capacity is set equal to the dynamic energy that would be in the system if the system behaved in a liner elastic manner only. The consumed dissipation potential amounts (according to equation 2) to

$$W_{dyn} = E_{el} = 2.1 \text{ kNm} \tag{3}$$

This internal work corresponds to only 7 % of the total dissipation capacity of the bridge girder that amounts to

$$W_{tot} = (M_u - M_y) \cdot \left[\frac{1}{2}(\alpha_p - \alpha_y) + (\alpha_u - \alpha_p) \right] = 30 \text{ MNm} \tag{4}$$

The remaining rotation may be calculated with this consumed dissipation potential using the work diagram of Figure 3. It amounts to $\alpha_{\text{x,en-bal}} = 0.018$. (Remark: Some resistance coefficient (of about 1.2) as partial safety factor should be considered for the dissipation capacity.)

In reality, the dynamic properties of the structural system change during the transition from pure elastic to elastic–plastic behaviour. This (virtual) elastic dynamic energy cannot entirely be built up. High damping due to early plastic deformations avoids the come up of large vibration energy in the case of resonance like excitation. Moreover, in the case of an impact, the flexibility due to the plastic reaction of the bridge structure constricts in an early stage the increase of kinetic energy. Therefore, equating the internal work with the energy that would accumulate for pure elastic behaviour leads to a result on the safe side.

A higher amount of plastic dissipation capacity however may be consumed when the dynamic excitation consists in several impacts on the bridge. In this case, the consumed dissipation capacity may be higher. However, the scenario considered is “occasional” with a very small probability of occurrence, i.e., several overloaded vehicles crossing the bridge one after the other is very unlikely to occur and may be neglected as an irrelevant ULS scenario.

Additionally, it must be noted that an accumulation of conservative assumptions have been made. Remaining deformations in the bridge girder are accepted in this (virtual) case at ULS, just like in the case of redistribution of internal forces in statically indeterminate systems.

4 DISSIPATION OF DYNAMIC EFFECTS AT ULS – DYNAMIC SIMULATION USING A SIMPLE ANALYTICAL MODEL

A more accurate result for the internal work is obtained by the following dynamic simulation. Figure 4 shows the simplified dynamic model. The two-mass oscillator represents the effective bridge mass for the first mode with the corresponding non-linear force-displacement behaviour. The vehicle is represented by a one-mass oscillator.

The effect of the static loads is sufficiently high such that the yielding level is reached (like in previous study (Figure 3)). The excitation consists in an application of a kinetic energy that corresponds to the maximum dynamic "bridge" reaction for pure elastic behaviour due to a dynamic amplification factor of $\Phi = 1.8$. (The vehicle is considered by its mass only, the suspension is neglected.)

The initial velocity v_0 for the two masses is calculated by equalising this kinetic energy with the maximum potential energy that corresponds to $\Phi = 1.8$. The initial velocity v_0 is applied on the two masses of the model in Figure 4.

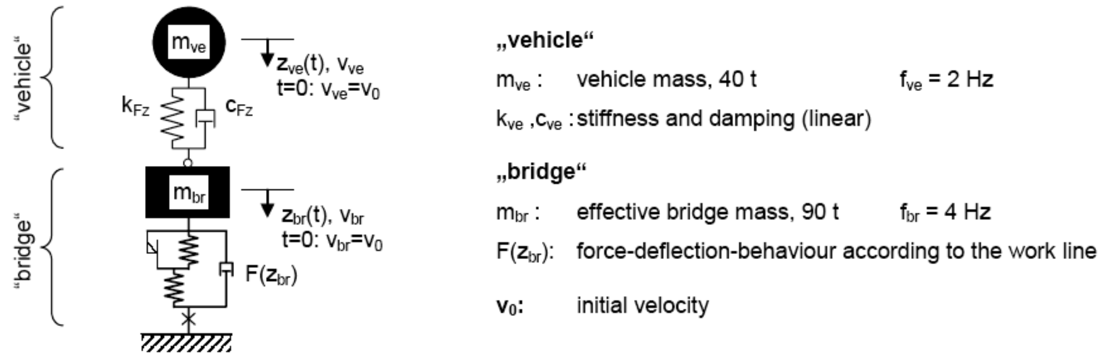

Figure 4: Dynamic model for the vehicle-bridge interaction at ultimate limit state

Figure 5 shows the response of the system in terms of displacements and forces. The displacement increases during the first 0.3s. Then, an oscillation occurs and remains around a constant value. This oscillation represents actually the remaining kinetic energy after partial dissipation due to plastic deformations. This behaviour is due to strain hardening; the elastic limit is now higher after the plastic deformation ($M_{y,1}$, Figure 6) which enables the storage of a part of the initially introduced kinetic energy.

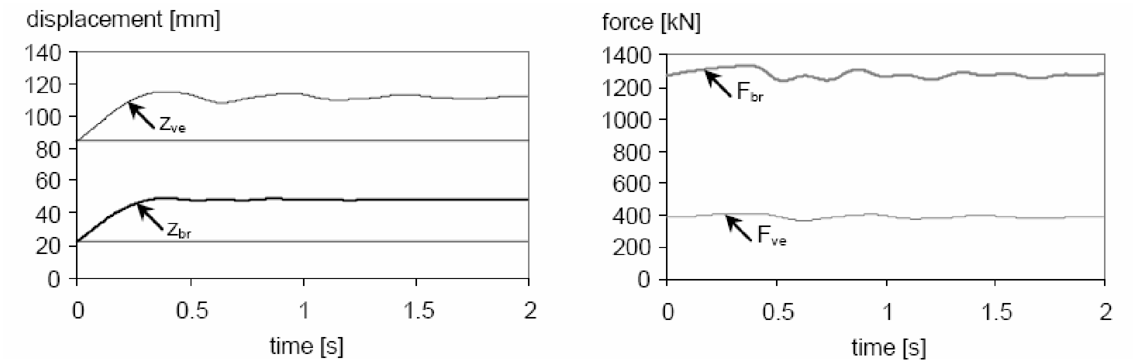

Figure 5: Displacements and forces as a function of time

The used dissipation capacity W_{dyn} as obtained from the simulation is indicated in the moment – rotation diagram of plastic hinge at mid-span of the bridge girder (Fig. 6). The remaining rotation amounts to $\alpha_{x,sim} = 0.012$.

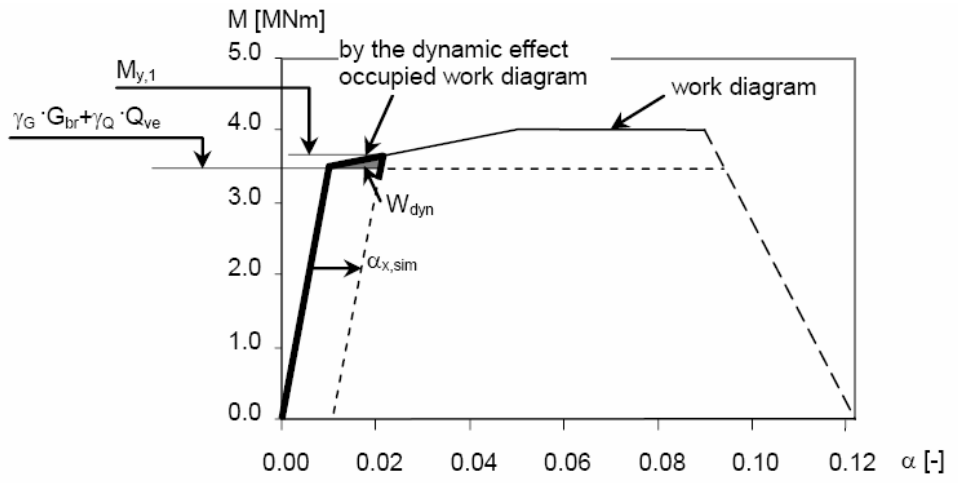

Figure 6: Work diagram of the plastic hinge with the result of the dynamic simulation.

From the dynamic simulation results that only

$$W_{dyn} = 0.9 \text{ kNm}$$

is consumed to dissipate the energy due to dynamic action effects. This corresponds to only 43 % of the value obtained by the simple energy consideration (Chap. 3).

One reason for this lower energy dissipation is the fact that the flexibility of the vehicle is considered in the dynamic simulation. Vehicle vibrations then store a certain amount of the dynamic energy, which reduces the amount of energy that must be dissipated by plastic deformations of the bridge structure. Furthermore, the bridge structure changes its dynamic properties in terms of fundamental frequency after yielding and early plastic deformations lead to rather high damping of the structural system (before the virtual elastic stationary state is reached), and kinetic energy is no longer entirely built up.

5 CONSEQUENCES FOR THE VERIFICATION OF STRUCTURAL SAFETY AT ULS

5.1 *Structural behaviour at ULS with significant deformation capacity*

The previous considerations and calculations indicate that only a small part of the remaining dissipation capacity (after taking into account energy dissipation due to the gravity effect and internal redistribution) is needed to dissipate the energy due to dynamic traffic action effects.

From this follows that in the case of plastic structural behaviour at ULS the maximum static action effect due to traffic loads does <u>not</u> need to be amplified by a factor for considering dynamic rail traffic action effects, or:

$$\varphi_{ULS} = 1.0.$$

This is valid for most structural elements showing significant plastic deformation at ultimate limit state, i.e. structural elements in reinforced and prestressed concrete as well as in steel.

Reliable numerical models are today available to conduct nonlinear analyses of structures (Plos et al. 2007) with the objective to determine the structural response necessary to evaluate the deformation capacity.

5.2 *Structural behaviour at ULS with small deformation capacity*

For failure modes with small deformation, i.e. punching of slabs or other shear-type failure modes, it is prudent to assume some amplification factor that implies relevant characteristics of elastic dynamic structural behaviour (see [Brühwiler 2007]) as well as the following findings:

- Only extremely high single carriage loads cause ULS relevant scenarios. This means that the amplification factor depends on the determinant length L_φ, i.e. the longer L_φ the smaller the amplification factor φ_{ULS} .
- In addition, many investigations show (f.ex. also in (Ludescher 2004) and (Herwig 2006)) that dynamic amplification is smaller with higher acting load.
- The main cause of dynamic effects is due to road or track irregularities. Assuming that the road or track is maintained periodically, the amplification factor should consider track irregularities typical for the quasi permanent state.

As a consequence, the amplification factor for failure modes with small deformation at ULS as shown in Fig. 7 is suggested based on the forgoing considerations.

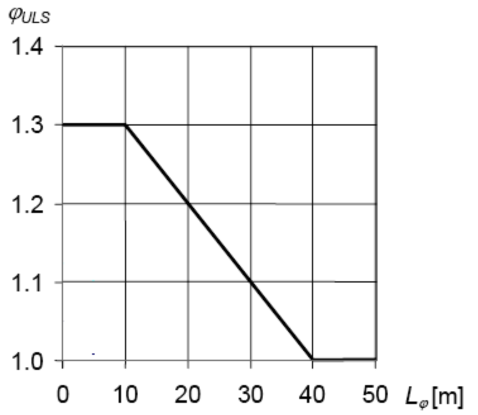

Figure 7: Dynamic amplification factor for failure modes <u>with small deformation</u>.

6 CONCLUSIONS

In the context of updating of traffic action effects on existing bridges, dynamic amplification effects are investigated and dynamic amplification factors are derived for the deterministic verification of structural safety at Ultimate Limit State of bridges.

In the case of significant plastic deformation of structural elements sufficient dissipation capacity is available. This means that the dynamic amplification factor may be set to $\Phi = 1.0$.

The present rational approach is simple and reasonably conservative. It most likely provides an important finding to demonstrate – in an efficient manner – that most existing bridges fulfil the requirements of structural safety when future traffic loads are increased.

The present approach is applicable for most bridge structures. In special cases, traffic measurements, nonlinear analyses to determine the structural response or dynamic numerical simulations for frequent traffic configurations could be performed to determine specific load models and dynamic amplification effects for particular bridge structures.

7 ACKNOWLEDGEMENTS.

The Swiss State Secretariat for Education and Research (SER) in the context of the European project "Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives" has financially supported this research.

8 REFERENCES

Brühwiler E., Herwig A. (2007) *Updated Rail Traffic Loads and Dynamic Amplification Factors*, Paper, International Conference "Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives", Wrocław, Poland, October 10-11, 2007.

SB-LRA (2007): *Guideline for Load and Resistance Assessment of existing European Railway Bridges.* Prepared by Sustainable Bridges - a project within EU FP6. Available from: www.sustainablebridges.net.

Ludescher H. (2004) *Berücksichtigung von dynamischen Verkehrslasten beim Tragsicherheitsnachweis von Strassenbrücken*, Thèse N° 2894, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland (in German).

Herwig, A. (2006) *Consideration of the effect of increased train loads for the fatigue examination of concrete bridges*, In Thomas Vogel, Nebojša Mojsilovi, Peter Marti (editors), 6th International PhD Symposium in Civil Engineering, Zurich, 23-26 August, SP-015, Zurich: IBK Publikation.

Herwig, A., (2008) *Reinforced concrete bridges under increased rail traffic loads – load carrying behaviour, fatigue behaviour and safety measures*, Doctoral thesis Nr. 4010, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.